



Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2013

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Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2013



R-Report

Edited by: S.B. Korsholm, S.K. Nielsen, J.J. Rasmussen
and C.M. Westergaard

April 2014

DTU Physics
Department of Physics



Abstract

The programme of the Research Unit of the Fusion Association Euratom – DTU, Technical University of Denmark covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. Within fusion technology there are activities on fusion materials research (Tungsten and ODSFS). Other activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2013.

Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2013

Report
2013

Edited by: S. B. Korsholm, S. K. Nielsen, J. J. Rasmussen and C. M. Westergaard

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Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in the early 2020ies. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. Fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, and presents considerable scientific and engineering challenges. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry.

In 2012 EFDA adopted a detailed and ambitious roadmap towards commercialisation of fusion power plants by 2050. This roadmap shows a clear path towards achievement of fusion. DTU participates in the internationally coordinated activities to develop fusion, with our activities being aligned and in full support of the roadmap strategy. We further see ourselves with a key role in facilitating the participation of Danish industries in the international fusion programme.

The fusion of hydrogen isotopes into form helium is the principle used in ITER. To obtain a large number of fusion events the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. ITER will use magnetic fields to confine the plasma. Two key issues in the final steps towards realising fusion energy production are our main drivers:

Improving energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy, demands a reduced energy transport out of the plasma, which principally is due to turbulence. Thus we work to understand and control plasma turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

Since January 2012 the activities within fusion plasma physics research are located within the Department of Physics (DTU Physics) as section for Plasma Physics and Fusion Energy (PPFE). Simultaneously the Research Unit for the Contract of Association is hosted by DTU Physics and the Association is termed EURATOM – DTU. The PPFE provides the main activities within the Research Unit. Additionally there are contributions to investigations of materials (Tungsten and ODSFS), socio economic studies and the potential for activities related to robotic handling are presently explored.

The main DTU contributions to fusion research in 2013 have been:

- 1) Models for investigating turbulence and transport. A better agreement between SOL modelling and experiments has been achieved, giving rise to better understanding of processes leading to flow formation at the edge SOL transition. DTU also worked on extensions of the validity range of gyrokinetic equations into that challenging region of a magnetically confined plasma.
- 2) Central to understanding the dynamics of fast ions is temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. DTU, in collaboration with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson

scattering (CTS) diagnostics at the ASDEX upgrade tokamak at the Max-Planck Institute for plasma physics in Garching (near Munich). Progress has been made towards readying the diagnostic for scientific exploitation and for extending the range of measured quantities, f.x. measuring the composition of the plasma fuel.

Organization

Association Steering Committee

- European Commission – DG Research & Innovation
 - Simon Webster, Head of Unit G.6, Fusion Energy – SC member
 - Vito Marchese, Unit K6, Fusion Association Agreement (until 31.05.2013) – SC member
 - Angelgiorgio Iorizzo, Unit G.6, Fusion Energy (since 10.06.2013) – SC member
 - Georges Bonheure, Unit G.6, Fusion Energy – SC expert
 - Mark Cosyns, Unit G.7, Administration and Finance – SC member
- Denmark - DTU
 - Jane Hvolbæk Nielsen, DTU Physics
 - Jens-Peter Lynov, DTU Nutech
 - Henning Bo Nicolajsen, DTU Physics

Association EURATOM-DTU

- Head of Research Unit
 - Volker Naulin from October 1 2012
- Financial contact person
 - Poul K. Michelsen

Danish representatives in EURATOM committees and contact persons

- DTC
 - Jens-Peter Lynov
- CCE-FU
 - Gorm Bramsnæs
 - Jeppe Søndergaard Pedersen (observer)
 - Volker Naulin
- EFDA Steering Committee
 - Volker Naulin
 - Jens Juul Rasmussen
- Governing Board F4E
 - Volker Naulin
 - Gorm Bramsnæs
 - Jeppe Søndergaard Pedersen (observer)
- F4E Executive Committee
 - Lisbeth Grønberg
 - Jeppe Søndergaard Pedersen (observer)
- Industrial Liaison Officer
 - Søren B. Korsholm
- High Performance Computer Contact Person
 - Anders H. Nielsen
- Public Information Officer
 - Søren B. Korsholm
- Remote Participation Contact Person
 - Anders H. Nielsen
- JET Contact Person
 - Mirko Salewski

- EU Task Force ITM
 - Anders H. Nielsen
- EFDA IPH Task Agreements
 - Volker Naulin
- Specialist Working Group on Microwave Diagnostics of ITPA Diagnostics TG
 - Søren B. Korsholm

Research groups

- **DTU Physics**
 Section of Plasma Physics and Fusion Energy, PPFE
 Head of Section Volker Naulin
 Host of the association EURATOM - DTU
- **DTU Management Engineering**
 Socio-Economical studies – Fusion in the Energy system
 Poul Erik Grohnheit
- **DTU Mechanical Engineering**
 Fusion Technology – Thermal stability of Tungsten
 Wolfgang Pantleon

1. Summary of Research Unit activities

The activities in the Research Unit are in **Fusion Plasma Physics**:

- *Theoretical and numerical turbulence studies.* Turbulence and the associated anomalous transport of particles, energy and momentum are investigated developing and using first principles based models. Application of the models is performed by numerical codes exploiting full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at partner associations. The activities are focused on topics related to edge and scrape-off-layer (SOL), i.e. the transition from magnetic confined plasma to plasma in contact with material interfaces. The work is performed in collaboration with EFDA partners and in particular with EFDA/JET.
- *Fast Ion Collective Thomson Scattering.* The research unit is developing and exploiting a fast ion collective Thomson scattering diagnostics at ASDEX Upgrade (AUG). With this diagnostic we obtain time, space and velocity resolved information about the energetic particles in the plasma as well as information on the plasma fuel composition. This project is carried out in close collaboration with the AUG team. The group is working towards being awarded the corresponding design task for the ITER device, which will demonstrate energy production from magnetic confinement fusion, and thus have specific need for diagnosing "hot" ions.

Other activities in 2013 have been:

- 1 Investigations in the properties of Tungsten as a material in fusion power plants.
- 2 Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES.
- 3 Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER.
- 4 Activities on public information about fusion energy. This includes development and presentation of the "Danish Fusion and Plasma Road Show".

The **global indicators** for the Research Unit in 2013 are:

Professional staff:	9.61	man-years
Support staff:	1.91	man-years

2. Plasma Physics and Technology

2.1 Introduction

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Plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true for the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. As solid state physics is involved in a broad range of applications, it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at DTU, and gives us access to placing our experimental equipment on large fusion facilities at, e.g., the Max-Planck Institute for Plasma Physics in Garching, Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area*. Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

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Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmospheres. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmospheres \times seconds and is currently one atmosphere \times seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant

fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. This is another of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, Germany.

2.2 Turbulence and transport in fusion plasmas

J. Madsen, V. Naulin, A. H. Nielsen, and J. Juul Rasmussen

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the “anomalous” transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore, it is of highest priority to achieve a detailed understanding of anomalous transport and of the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

The activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are involved in the EFDA-JET program. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well as defining the ITM data structures. A. H. Nielsen is deputy leader for project IMP4. We have a significant involvement in the EFDA ITER Physics tasks (IPH). V. Naulin is deputy chair of the topical group transport.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students.

The work carried out through 2013 includes:

Activities within TG Transport are discussed in Secs. 2.2.2. This covers participation in the planning and reporting of the TG Transport activities together with participation in specific tasks on the modeling and measurements in the SOL/edge region of toroidal devices.

Examples of the involvement in the ITM activities are provided in Sec. 2.2.3. The emphasis is here on the involvement in IMP4 on validation and benchmarking of codes as well as developing the Kepler workflows.

Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas are continued by participating in experimental investigations and applying edge/SOL turbulence codes. These investigations are an integral part of our contributions to the IPH projects, which are directed towards the modelling and understanding of EDGE/SOL turbulence and transport. Section 2.2.4 describes investigations related to the transport through the SOL and the divertor heat load. Specifically we have applied the ESEL code to evaluate experimental probe measurements of flow profiles in the SOL and the edge shear layer region. Investigations of the propagation of hot blob-filaments are performed by means of a new numerical model, HESEL, accounting for the full ion dynamics, see Sec. 2.2.5. The development of a 3D global turbulence SOL code module is described in Sec. 2.2.6. The work was performed under an IPH task, headed by Anders H. Nielsen. We have organized two workshops at DTU Physics on this topic, a project kick-off workshop June 11 – 12, mainly on (sheath-) boundary conditions, and a workshop 3DiESEL in November 4 - 8 on the model and specific code development. Section 2.2.7 provides a description of the theory of HESEL model, which is based in the ESEL and accounts for the full ion dynamics. The HESEL code is applied to model the so-called dithering phase now routinely observed in experimental investigations of the L–H transition in Sec. 2.2.8. The results appear to be in agreement with the experimental observations.

The ESEL code has been applied to model the SOL dynamics in the MAST device at CCFE (Sec. 2.2.9) and accurate agreement with experimental observations have been obtained for the statistics of the turbulence, the structure of the characteristic blobs, and the density and pressure profiles in the SOL. The structure of individual blobs as they expand toward the divertor is discussed in Sec. 2.2.10 as a contribution to the 3D SOL modelling effort.

In Sec. 2.2.11 we have investigated the interchange driven convection of blobs using a full-f gyrofluid model, i.e., including the influence of finite ion temperature and showing a significant of finite Larmor radius (FLR) effect on the filament dynamics. Section 2.2.12 is concerned with the investigations of Lagrangian invariants in gyro-fluid models and the derivation of the associated Turbulent Equipartition States, TEP, states. The so-called low-dimensional Predator-Prey models for the L-H transition has been investigated in detail in Sec. 2.2.13 revealing the full bifurcation structure and the relation to the various types of L-H transitions. In Secs. 2.2.14 and

2.2.15 we describe experimental investigations of ELM filaments and their distinction from dithering events in the dithering phase of the L-H transition in the EAST tokamak. These investigations supplements the investigations under the IPH tasks of filamentary dynamics in, e.g., the Asdex Upgrade device. Finally, Sec. 2.2.16 describes new attempts to describe non-local transport in magnetically confined plasma by combining concepts from turbulence development with the so-called Self-organized Criticality, SOC, concept.

The involvement in the JET work program is summarized in Secs. 2.2.17 and 2.2.18. It comprises a novel approach for experimental investigations of turbulent transport by applying modulated gas-puffing.

2.2.1 EFDA tasks in the turbulence group

J. Madsen, V. Naulin, A.H. Nielsen, Y. Ning, J. Juul Rasmussen

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During 2013 the turbulence group was involved in the following EFDA ITER physics activities:

- **WP13-IPH-A06-P1-01/DTU:** SOL transport and divertor heat loads in steady state and unmitigated ELMs

The task was performed in collaboration with the Associations: ÖAW/Innsbruck, ENEA_RFX/Padova, MHEST/Ljubljana, and IPP/CR Prag. The activities comprised measurements of the edge-SOL in inter-ELM and L-mode using the mid-plane manipulator. The probe measurements were supported by numerical investigation of synthetic probe measurements.

The main contributions of our group are described in sections 2.2.4, see also 2.2.9 for related investigations.

- **WP13-IPH-A06-P2-01/DTU:** Active control of ELMs and the associated divertor heat loads.

The task was performed in collaboration with the Associations: ENEA-RFX/Padova and ÖAW/Innsbruck. The activities comprised investigations of ELM/blob dynamics and transport in the Scrape-off-Layer in addition to cross-machine experiments using RMPs in order to suppress/mitigate/control ELMs.

The main contributions of our group are described in 2.2.5, see also 2.2.7 for related investigations

- **WP13-IPH-A10-P2-01/DTU:** Development of turbulent SOL code

The task was performed in collaboration with the Association: CCFE/UK. The activities comprised development of 3D global turbulence SOL code module in simple geometry including sheath boundary conditions ready for benchmarking with 1D and 2D SOL fluid codes. They further include the definition of standardized benchmark cases.

The main contributions of our group are described in 2.2.6, see also 2.2.10 for related investigations

2.2.2 Topical Group Transport co-chairmanship

V. Naulin

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The task of the topical group transport has been to

- Ensure that the overall EFDA Work Plan and Work Programme objectives are adequately translated into specific /detailed scientific and technical objectives in the allocated area(s).
- Concentrate European research on the most urgent problems in the respective field for ITER and future devices, and propose scientific and technological concepts to overcome these problems.

The work of the topical group was focused on the EFDA work programme 2013, with preparation of the selection of contributions to the work programme. During a meeting at Garching in January 2013 with the corresponding CSU ROs the selection was proposed, discussed and adjusted to the received input. In the discussions on the EUROFUSION proposal the administrative recommendations of the topical group were formulated, specifically with respect to mobility support, and initially discussed at the Frascati HoRU meeting 20.11.2013 and later in written form send to the interim programme manager Francesco Romanelli. During the year the TG T was involved in discussing and recommending transport issues for the formulation of the work programme.

The preparations for the 2014 EU-US TTF were started and the early selection of place, topic and prospective session leaders was performed.

2.2.3 Integrated Tokamak Modelling Engagement

A.H Nielsen, B.D. Scott and the ITM-IMP4 team (*IPP-Garching, D)*

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The engagement in the Integrated Tokamak Modelling (ITM) has been concentrated in the project IMP4 in which DTU holds the deputy project leader position. Project #4 is responsible for numerical codes and associated Kepler workflows for instabilities, turbulence, and transport, as well as standards are maintained for the simple modules commonly used in transport modelling codes.

The activities in 2013 were focused on interfacing to experiments using JET data within ITM Kepler workflows, porting new experimental data into the ITM database, progress on general implementation of modules into European Transport Solver (ETS) workflows and incorporation of standard transport and neoclassical models into various ITM workflows.

During 2013 the highlights and achievements of IMP4 were

- 3 JET discharges have been uploaded to ITM-IMP4 database. It is foreseen that they will serve as benchmark cases for numerical edge and core codes under WP-CD from 2014.
- Development of a Kepler workflow, see Figure 1, to extract experimental measurements, run an edge simulation, in this case ESEL, and output synthetic probe results to Langmuir CPO. Comparison of experimental and simulation data shows a good match see Figure 2.
- Most of the IMP4 codes are now implemented on the new Gateway using 4.10a. A number of neoclassical codes can be found in the toolbox: NEOWES, NEOART and NCLASS.

- NEOART runs on test cases from JET (77922/2), ITER (35441/6) and DEMO1 (2/12).
- Actors for GLF23, RITM, WEILAND, EDWM and MMM model are available.

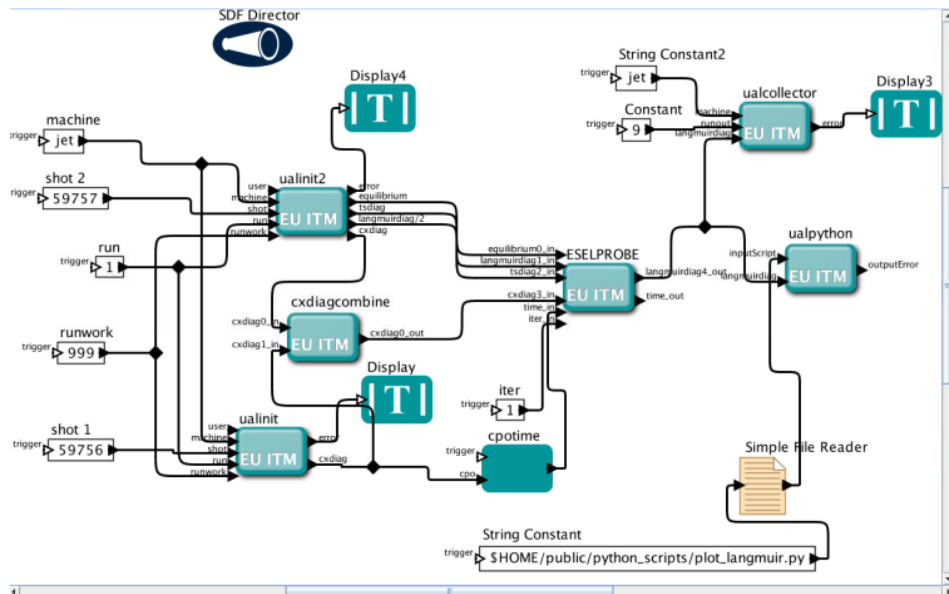


Figure 1. A Kepler workflow which generates synthetic Langmuir probe data. The workflow uses the turbulence actor, ESEL and reads data from two separate JET shots, #59757 and #59756

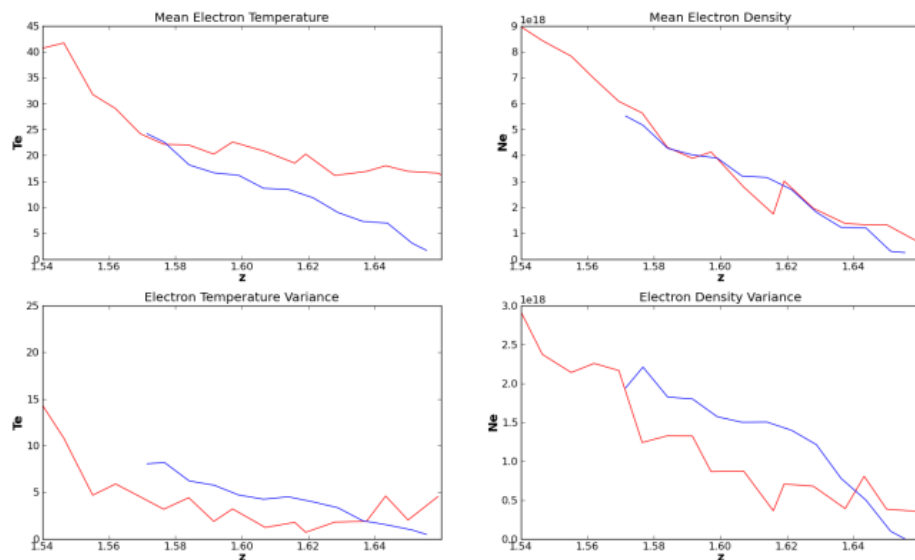


Figure 2. Output from the workflow in Figure 1 in form of radial profiles of mean values and relative fluctuations for the electron temperature (eV) and density (m^{-3}). Red and blue curves are JET and ESEL data, respectively.

DTU was directly involved in the project of including the numerical code ESEL in a Kepler workflow to generate synthetic Langmuir probe data based on JET experimental data, see

Figure 1. During execution of the workflow, the SOL plasma parameters were extracted from Langmuir CPO. The experimental data originate in this case from two nearly identical JET shots, #59757 and #59756, where the latter holds the ion temperature from charge exchange diagnostic and the first all other parameters. These parameters were passed as input to ESEL and the code was then executed on the Gateway Linux cluster in batch. Synthetic probe data were generated during simulation and written to the Langmuir probe CPO to be used for later analysis. The results of the simulations and experiments are plotted in Figure 2 for comparison. The agreement is observed to be satisfactory, but the simulation predicts a lower level of the mean values of the temperature and a higher fluctuation level of the density than observed in the experiment. This project will be continued under WPCD in 2014, also using AUG data.

2.2.4 Determining the poloidal velocity in the SOL of magnetized plasma

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Precise determination of the poloidal velocity in the edge and SOL on fusion machines is essential for e.g. the investigations of the transport particle and heat transport from the edge, into the Sol and finally along the magnetic field lines onto the divertor. This project is part of the EFDA Task, WP13-IPH-A06-P1-01.

The ESEL code was used to simulate the EDGE-SOL region at the outboard mid-plane of AUG, with parameters obtained from the experiment. Poloidal and radial arrays of virtual probes consisting of point-probes were used to simulate the tips of the pins of the experimental probe head and the recorded signals. The virtual probes measure the basic plasma fields such as density, n , electron temperature, T_e , electric potential, V_{pl} , and the two velocity components, V_p and V_t . From these fields one can easily obtain the experimental obtained field, floating potential, $V_{fl} = V_{pl} - \alpha T_e/e$ and ion saturation current, $I_s \sim n \sqrt{T_e}$. Here $\alpha \sim \ln(I_{es}/I_{is})$ takes the value of 3.4 for a deuterium plasma and 0.5 for an emissive probe. Thus, we can compare these values with the ones obtained from the probe arrays.

We have applied the results from the simulation to test the three methods used in the experiments to determine the poloidal velocity V_p (see [1]):

- 1) Determining the ExB drift from two radially separated probes, using $E_r = (V_{fl,1} - V_{fl,2})/dx$, with dx being the radially distance between the involved two probes.
- 2) From the cross-correlation (CC) of the signals of the two poloidally separated ion-biased probe pins and of two floating probe pins, this provides the time lag for maximum CC. For this method we must assume that the ExB velocity is dominating any phase velocity of the perturbations used for cross correlation, i.e., Taylor's hypothesis applies.
- 3) From the conditional-averaging (CA) of the same signals as for the CC method, which provide a time lag for maximum of CA, and we obtain V_p similarly to method 2.

Applying the first method the ExB velocity is evaluated from the floating potential at two radially separated probes ($dx=3$ mm as in the experiment) for different values of α and compared with the ExB velocity directly obtained from the simulations in the position between the two probes. It is observed that the electron temperature strongly influence the E-field and thereby the ExB velocity. The functional form of the profiles resembles the real velocity profile but with a much lower value, approximately 50 % lower. For $\alpha=0$, i.e., the probes measure the plasma potential,

the measured ExB velocity does also not match the real velocity profile due to the probe separation.

For the two other methods 2) and 3) we did not find much difference for varying α , thus, for these methods an array of cold Langmuir probes provides approximately the same result as ideal probes. This applies to the case where we use the floating signal as well as the case applying the ion saturation current signal. It appears that the two methods provide results which are comparable with real velocity profile, see Figure 3, with method 3) being more accurate than method 2. More analysis is needed before a conclusion can be reached and the project is ongoing and will be a focus area for both involving groups in EUROFUSION in 2014.

[1] F. Mehlmann, S. Costea, V. Naulin et al., 40th EPS Conf. Plasma Physics. Espoo Finland June 2013. P5.187

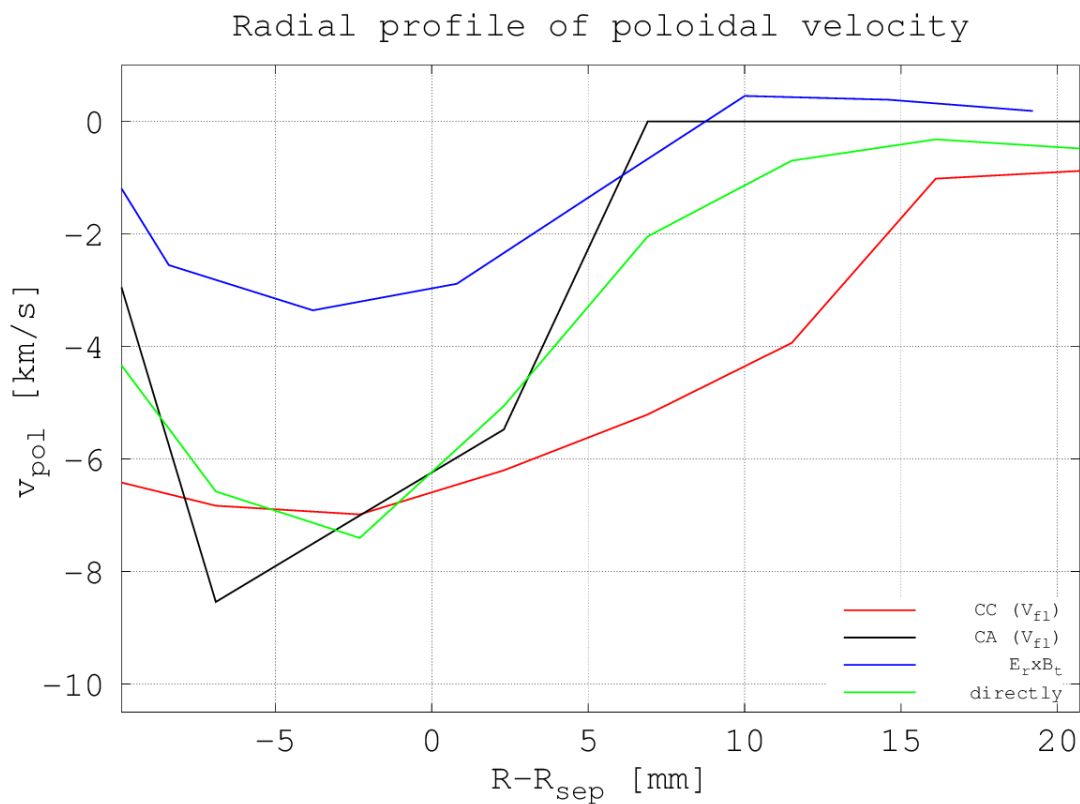


Figure 3. Radial profile of poloidal velocity determined by the three methods from the floating potential, $\alpha = 3.2$ The green curve shows the real ExB velocity.

2.2.5 Simulations of blob and filament propagation in the SOL applying the HESEL model.

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We have investigated the propagation of warm blobs and filaments in the Scrape-off-Layer (SOL) of magnetically confined plasma. The investigations are based on numerical solutions by

applying the newly developed HESEL code [1]. This project is part of the EFDA Task, WP13-IPH-A06-P2-01 performed in collaboration with ENEA-RFX and ÖAW- Innsbruck.

The HESEL (Hot Edge SOL ELectrostatic) code is based on a four-field Braginskii fluid model described in Sect. 2.1.2. It includes the evolution of density, electron and ion pressure and generalized vorticity, which combines the ExB vorticity and the ion diamagnetic vorticity. The code is solved on a 2D domain that includes the edge region with closed field lines and the SOL with open field lines. The domain is located on the out-board mid-plane of a tokamak. The parallel dynamics is parameterized, modelling the sheath boundary conditions in the SOL. An important issue is that the dynamics is global in the sense that profiles and fluctuations are modelled on the same footing. This is an essential feature for a proper description of the SOL dynamics, where the fluctuations in, e.g., density and pressure, attain amplitudes that are comparable with or even larger than the mean values – “the profiles”.

HESEL is an extension of the ESEL model and the results from HESEL have been verified by ESEL simulations in the limit of cold ions. HESEL allows for an estimate of the power flux into the SOL and thereby making possible the estimates of power deposition profiles.

Here we present results for the propagation of blob/filament structures in the evolution of Edge-SOL interchange driven turbulence. We use parameters from typical medium sized tokamaks, as, e.g., ASDEX Upgrade and EAST. An example of the results is shown in Figure 4. In the left panel we show a snapshot of the spatial structure of density, ion and electron pressure during the development of a blob. The characteristic blob structure is clearly observed in all three fields. In the right hand panel we show the conditionally averaged wave-forms of the density, electron and ion temperature, and the potential. The applied condition is obtained from the turbulent particle flux.

We observe that the density wave-form is only changing very slowly when the blob propagates through the SOL, similarly for the electron temperature, while the ion temperature is decreasing slightly faster than the electron temperature (see Figure 5). This may be explained due to a faster perpendicular diffusion of the ions as compared to the electrons. Thus, the faster parallel electron diffusion is surpassed by the faster perpendicular ion diffusion in the localized filamentary structures. For the temperature profiles it is observed that the electron temperature has the largest decay. The results are in qualitative agreement with observations and modelling of blob dynamics from AUG [2]. A detailed benchmarking of the HESEL model is in progress. It should be noted, however, that there are only few measurements available of the ion temperature development.

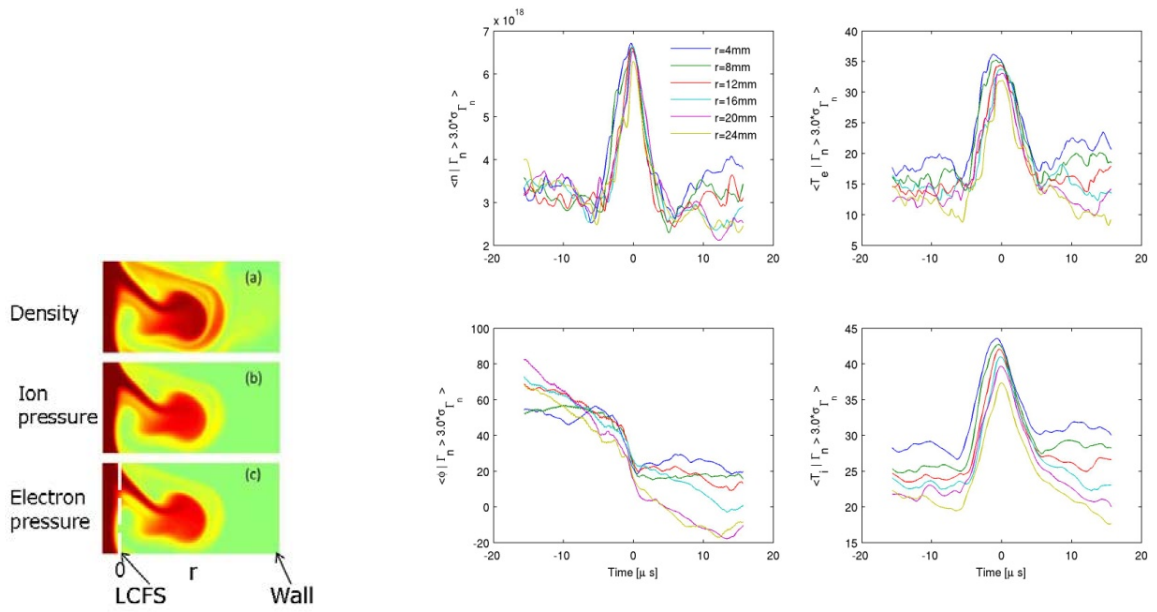


Figure 4. The evolution of a blob/filament structure for typical parameters for an AUG-size Tokamak. Parameter values at Last Closed Flux Surface: $n = 5 \times 10^{19} \text{ m}^{-3}$, $T_e = 30 \text{ eV}$, and $T_i = 40 \text{ eV}$. The left hand frame shows the evolution of the density, ion, and electron pressure in a blob/filament. The right hand side frame shows the evolution of the conditional sampled blobs at different radial positions in the SOL, with distance measured from the LCFS. The applied condition is on the particle density flux.

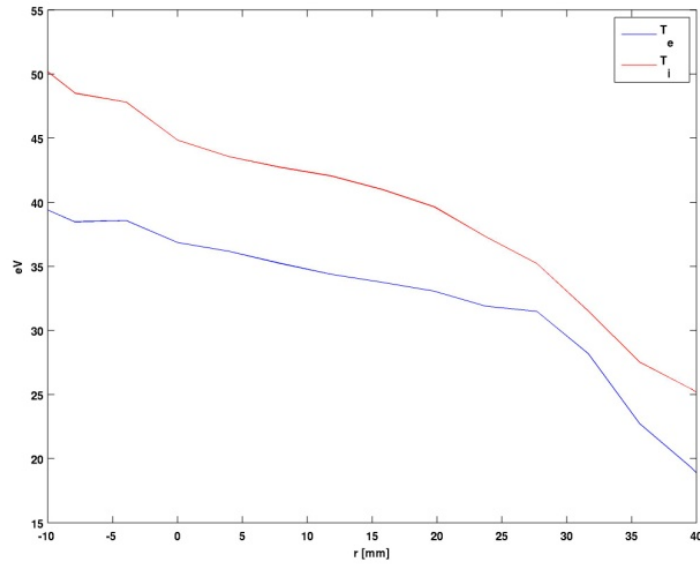


Figure 5. The evolution of the maximum blob temperatures during the propagation throughout the SOL

- [1] A.H. Nielsen, J. Madsen, G.S. Xu, V. Naulin, J. Juul Rasmussen, N. Yan, 40th EPS Conf. Plasma Physics. Espoo Finland June 2013. P5.173.
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2.2.6 Development of a turbulent SOL code

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This work is part of the task WP13-IPH-A10-P2-01/CCFE/PS and was performed in close collaboration with the CCFE (WP13-IPH-A10-P2-01/CCFE/PS). The objective was to develop a 3D global turbulence SOL code module in simple geometry and which should include sheath boundary conditions ready for benchmarking with 1D and 2D SOL fluid codes. Secondly we define standardized benchmark cases to be used in this and future projects.

Both groups implemented the so called CYTO mathematical model, see [1], which evolve the four fields: vorticity, logarithm of the plasma density, N , parallel electron and ion velocity, V and U respectively, in a straight magnetic field. The geometry of the problem is assumed to be a slab box representing half of the SOL. We use sheath boundary conditions in the parallel direction and for one of the perpendicular directions we use periodic boundary conditions, while we for the other perpendicular direction assume Neumann boundary conditions for all the fields, except for vorticity and electrostatic potential, which is fixed to zero

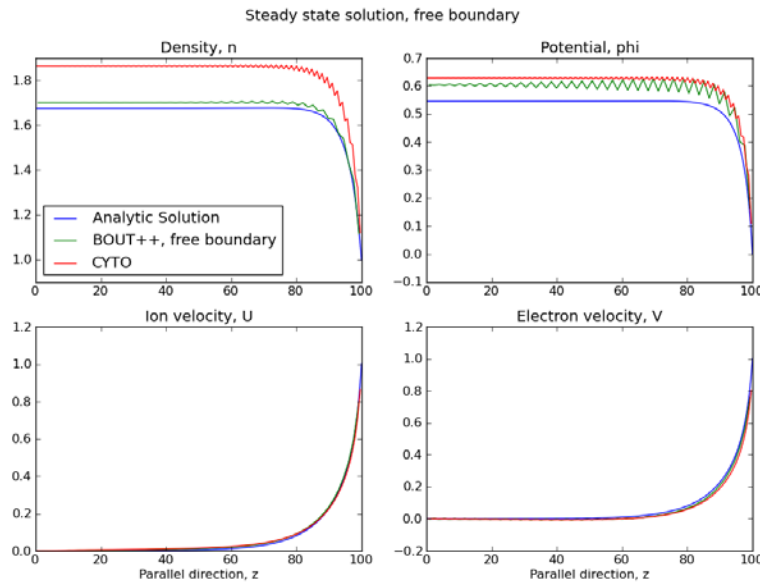


Figure 6. Parallel profiles from simulations of CYTO and BOUT++ compared to the analytical solution, for the benchmark case 1 (KIWI device).

The DTU group was using the CYTO framework, whereas the CCFE group included the model in the BOUT++ framework. Generally, we found good agreements between the codes, and in 2014 we will look more into the BOUT++ framework as a platform to develop more complete 3D SOL codes.

The first benchmark case is a cold plasma in a small domain, resembling the KIWI device. The domain is a squared box of $10 \times 10 \times 100 \rho_s$ (ρ_s is the typical scale size – the ion Larmor radius at the electron temperature) and plasma parameters are: electron temperature 2 eV, ion temperature 0.03 eV, density $0.5 \cdot 10^{17} \text{ m}^{-3}$, magnetic field 0.07 T. The case was used to compare the two codes and results of this comparison can be observed in Figure 6 and Figure 7. The second benchmark case is a plasma with fusion relevant SOL plasma parameters. Here we considered a much larger domain in of a squared box of $100 \times 100 \times 10000 \rho_s$ and with plasma

parameters: electron and ion temperature 20 eV, density $1.5 \cdot 10^{19} \text{ m}^{-3}$, magnetic field 2.0 T. The benchmark was defined in detail and initial simulations were performed in both groups, but due to the complexity of the problem no firm conclusion is reached as yet.

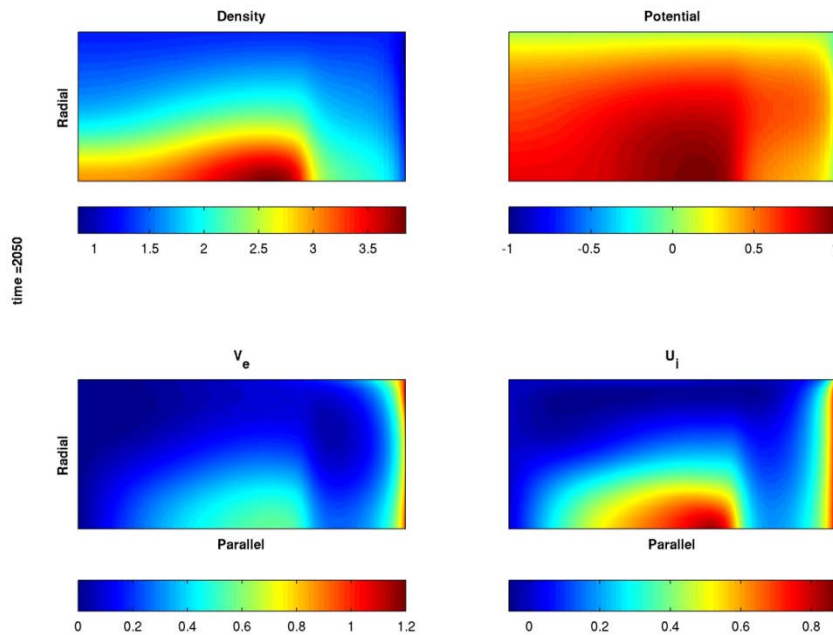


Figure 7. CYTO simulation showing a snap shot of the r - z cross section for the KIWI case. A large blob, with a density amplitude of 10 times the background, has been inserted upstream at $time=2.000$. A shock front is clearly seen in front of the blob, as it propagates towards the limiter.

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2.2.7 HESEL model – theoretical developments

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The HESEL model is an extension of the electrostatic SOL turbulence model ESEL [1]. Compared with ESEL the following improvements have been added to the HESEL model: 1) the ion pressure is evolved dynamically with the same level of sophistication as the electron pressure. 2) The vorticity equation includes the ion inertia response to the ion diamagnetic drift, which essentially is how finite Larmor radius effects enter drift fluid models [2]. 3) The collisional terms, taken from the Braginskii fluid closure [3], have systematically been included in the drift fluid solution of the perpendicular part of the momentum equation. This systematic treatment of collisional effects implies that the model now perfectly conserves energy, e.g., viscous losses of perpendicular energy due to ion–ion collisions appears as an energy source in the ion pressure equation etc. 4) Sheath boundary conditions have been parameterized through a sheath damping term in the vorticity equation.

The profile evolution, the generation of mean flows and the energy exchange has been investigated analytically. The investigations demonstrate that the introduction of generalized vorticity, again essentially including lowest order FLR effects, complicate the usual picture of mean flow generation and energy exchange mechanisms. The Reynolds stress is no longer the

only source of mean flows, but has an additional component, which is related to gradients in the ion pressure. Similarly, the usual interchange effect, which transfers energy between thermal energy and kinetic energy due to finite compression of the diamagnetic flux, is accompanied by an additional transfer terms, which is active when the electron and ion pressures are unequal. Our hope is that these theoretical considerations can lead to an improved understanding of profile formation and mean flow generation. Furthermore, these investigations are also relevant for gyrofluid and gyrokinetic models, because identical momentum and energy transfer mechanisms are present in those models, but are readily recognizable because gyrofluid moment fields and gyrokinetic distribution functions are functionals of several physical quantities. As an example the ion gyrofluid, gyro-center density is a function of particle density, vorticity, and ion pressure.

[1] O.E. Garcia, V. Naulin, A.H. Nielsen, and J. Juul Rasmussen, J. Juul, *Phys Plasmas*, **12**, 062309 (2005).

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2.2.8 Numerical simulations of transition to high confinement regime in a magnetically confined plasma

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An outstanding issue in contemporary magnetic fusion research is the understanding of the triggering mechanism for the transition from the Low (L-mode) to the High (H-mode) confinement regime, which ITER - the next generation international fusion experiment - will rely on to achieve the goal of ignition. Although the H-mode is routinely achieved in a multitude of magnetic confinement devices since the first observation more than 30 years ago [1] the transition still lacks full theoretical explanation and predictive modelling.

We have investigated the transition by using a numerical model based on the first-principle fluid model, HESEL (Hot Edge-Sol-Electrostatic) [2]. The model is an extension of the so-called ESEL model and is a four-field Braginskii model including generalized vorticity, density, electron and ion pressure equations. The 2D domain includes both open and closed field lines and is located at the out-board mid plane of a Tokamak.

The results are in good agreement with recent experimental findings, particularly from the Experimental Advanced Superconducting Tokamak – EAST [3]. This includes the dynamics of the oscillatory intermediate I-phase, appearing between the L- and H-mode, and the phase relations of the triggering events in response to a slow ramp up of the input power to the plasma. These results mark an essential step from zero-dimensional and one dimensional models with free parameters for describing the L-H transition. And hold promises of developing a full predictive modelling of the L-H transition, which is an essential ingredient in understanding and optimizing future fusion devices and a future fusion power reactor.

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2.2.9 ESEL simulations of MAST plasmas

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The L-mode interchange turbulence in the edge and scrape-off-layer (SOL) of the tight aspect ratio tokamak MAST was investigated numerically. The dynamics of the boundary plasma were studied using the 2D drift-fluid code ESEL, which previously had shown good agreement with large aspect ratio machines.

The MAST discharge was diagnosed with a reciprocating arm equipped with a Gundestrup probe. We performed a detailed comparison of the average and statistical properties of the simulated and experimental ion saturation current and found good agreement in the time-averaged radial profile, in the probability distribution functions, see Figure 8, and in qualitative features of the signals such as the shape, duration and separation of burst events, see [1]. These results again confirm the validity of the simple interchange model used and help us to identify where it can be improved. Also, the simulated data was used to assess the importance of the temperature fluctuations on plasma potential and radial velocity measurements acquired with Langmuir probes. It was shown that the correlation between the actual plasma quantities and the signal of the synthetic diagnostics was poor, suggesting that accurate measurements of the temperature fluctuations are needed in order to obtain reliable estimates of the perpendicular fluxes.

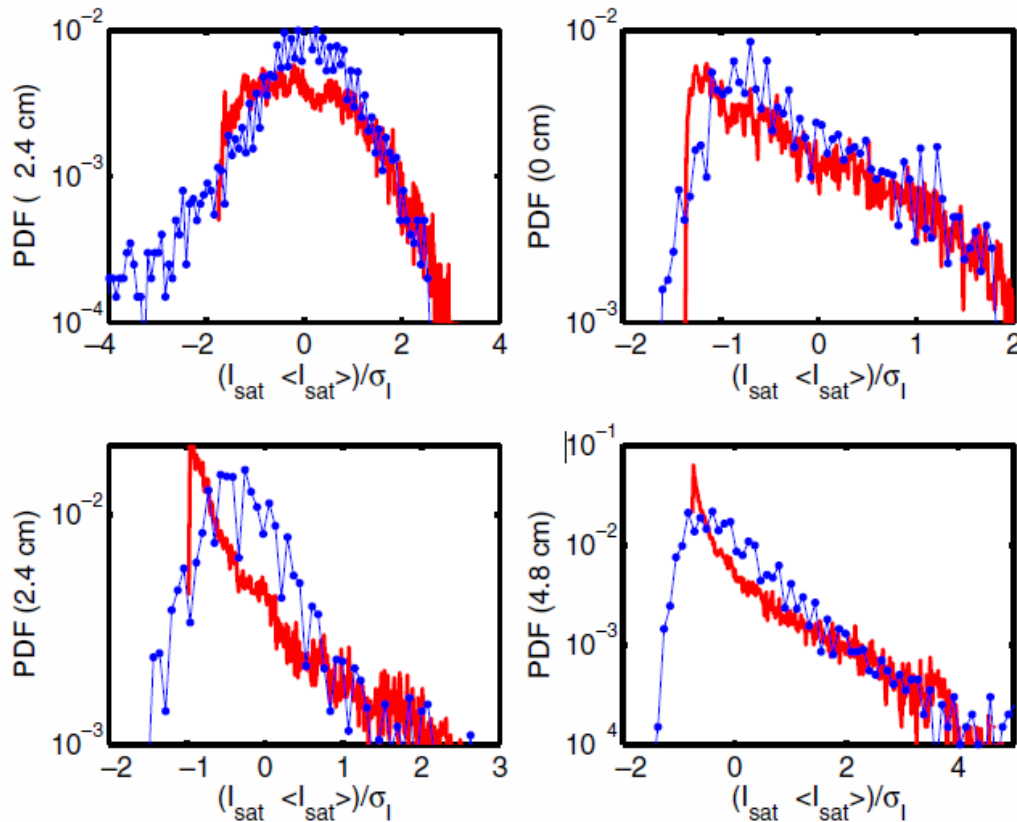


Figure 8. PDF of I_{sat} calculated in four radial locations for the experimental measurements (thin blue line with markers) and the ESEL (red lines).

The numerical code ESEL are also used to construct power scaling laws for the characteristic decay lengths of the temperature, density and heat flux at the outer mid-plane, see [2]. Most of the results obtained were in qualitative agreement with the experimental observations, despite the known limitation of the numerical model. Quantitative agreement was also obtained for some exponents. In particular, an almost linear inverse dependence of the heat flux decay length with the plasma current was recovered. The relative simplicity of the theoretical model used allows one to gain insight into the mechanisms determining the width of the SOL.

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2.2.10 Development of plasma blob structures in the scrape-off-layer in a Tokamak plasma with divertor geometry

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The transport of particles, momentum and energy into the Scrape-off-Layer, SOL, of Tokamak plasmas is known to be dominated by turbulence induced transport, which is found to be strongly intermittent and largely carried by convected filamentary structures, often referred to as plasma blobs. The blobs take the form lumps of plasma with increased density and temperature. They are formed near the Last Closed Flux Surface (LCFS) on out -board mid-plane of the Tokamak plasma. They move radially out through the SOL and simultaneously expands along the magnetic field lines taking the shape of filaments of hot plasma stretching towards the divertor plates. The blobs are thus responsible for the main deposition of particles and energy on the divertor plates and possibly on the walls of the plasma vessel. In order to predict the power deposition it is essential to understand the blob dynamics and especially how a blob having an approximately circularly cross section perpendicular to the magnetic field at the mid-plane is transformed when mapped along magnetic field lines toward the divertor region. We have investigated the structure of individual blobs as they expand toward the divertor. The results show that the cross section of the blobs are strongly modified due to the sheared magnetic field, the initial circular cross section gets strongly elongated, however, the cross section area is roughly conserved as the main magnetic field component – the toroidal component - has an almost constant magnitude. In Figure 9 we illustrate the blob structure along the magnetic field lines for the case of the magnetic field configuration of ITER [1]

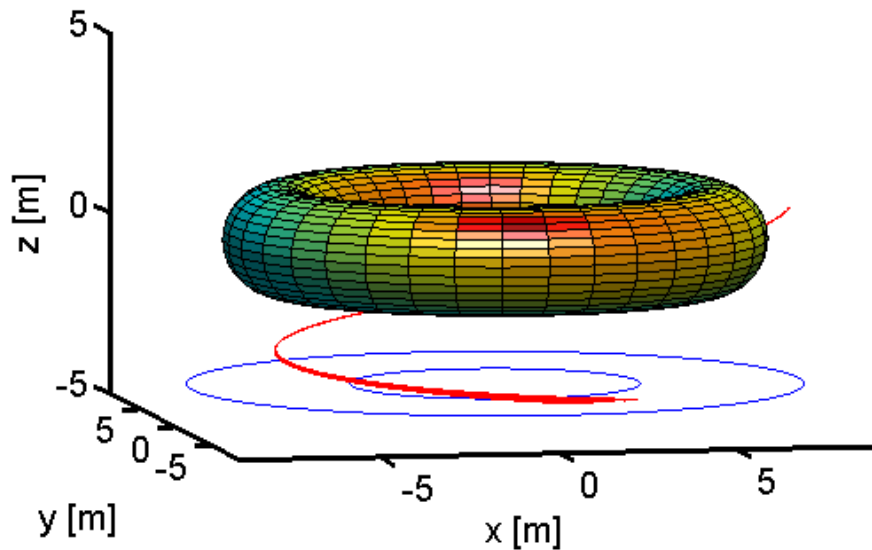


Figure 9. Mapping of blob in the ITER magnetic configuration. The blob has a circular cross section at the outboard mid-plane. A torus is drawn to visualize the position of the plasma, but it does not reflect the real D-shape of the plasma. The blob mapping is the red lines and a simplified plane divertor is shown by the two blue circles.

2.2.11 Interchange driven convection of high amplitude filaments with finite ion temperature in the scrape-off layer region

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The cross-field transport of particles, momentum and energy in the scrape-off region in Tokamak plasmas is dominated by turbulent transport. Plasma filaments, often referred to as blobs, carry a significant part of the total transport. Blobs are localized, coherent structures mostly born in the vicinity of the last closed flux surface at the outboard mid-plane. The blobs are convected radially from the edge region into the SOL. As the blobs are convected collisional diffusion and parallel convection are able to deplete the blobs so the amplitude fluctuation levels, relative to the background SOL region plasma, are often well above unity [1]. The plasma blobs have finite ion temperature and it is often so that the ion to electron temperature ratio is above unity due to parallel electron heat conduction and ionization of neutrals.

In this work we have investigated the interchange driven convection of blobs using a full-f gyrofluid model [2]. Full-f gyrofluid models are characterized by including finite Larmor radius (FLR) effects and simultaneously being valid when the fluctuation amplitude level is high. Previous similar investigations, e.g., [3,4] invoke the so-called “thin-layer” approximation, which effectively fixes the ion inertia to a constant value irrespective of the actual local ion mass density. Other investigations relax the thin layer approximation but neglect FLR effects, e.g., [5].

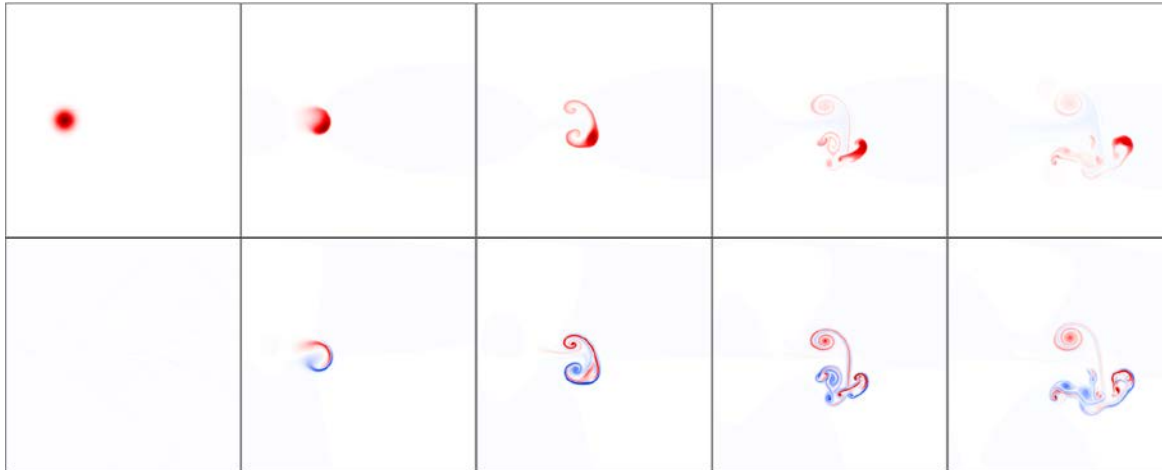


Figure 10. Contour plot showing particle density in the top row and vorticity in the bottom row. Ion to electron temperature ratio is 2, blob width is $10 \rho_s$, and the particle density amplitude is twice the background level. The columns are temporarily separated by 10 inverse interchange rates

The investigations were carried out using computer simulations of seeded blobs in a 2D plane perpendicular to the magnetic field at the outboard mid-plane. The simulations reveal that FLR effects dramatically change the nature of interchange driven blob convection. The blobs remain coherent as a consequence of the ion gyro-averaged ExB drift and the ion gyro-averaged charge contribution. Effectively, these FLR effects reduce mixing and stretching of the blob. Figure 10 shows contour plots from a particular simulation of a seeded blob in the plane perpendicular to the magnetic field at the outboard mid-plane. The convection changes from the cold ion inertial regime to the FLR effect dominated regime where blobs stay coherent when the ratio of the ion gyro-radius to the characteristic blob gradient length scale exceeds 0.2 as demonstrated in Figure 11. The increased radial blob transport is important for predictions of the SOL widths, and hence required if heat loads to the divertor and in general plasma facing components is to be calculated correctly. Therefore, the inclusion of FLR effects in modelling edge and SOL turbulence is essential. A paper reporting on these results is planned to be submitted for publication early 2014.

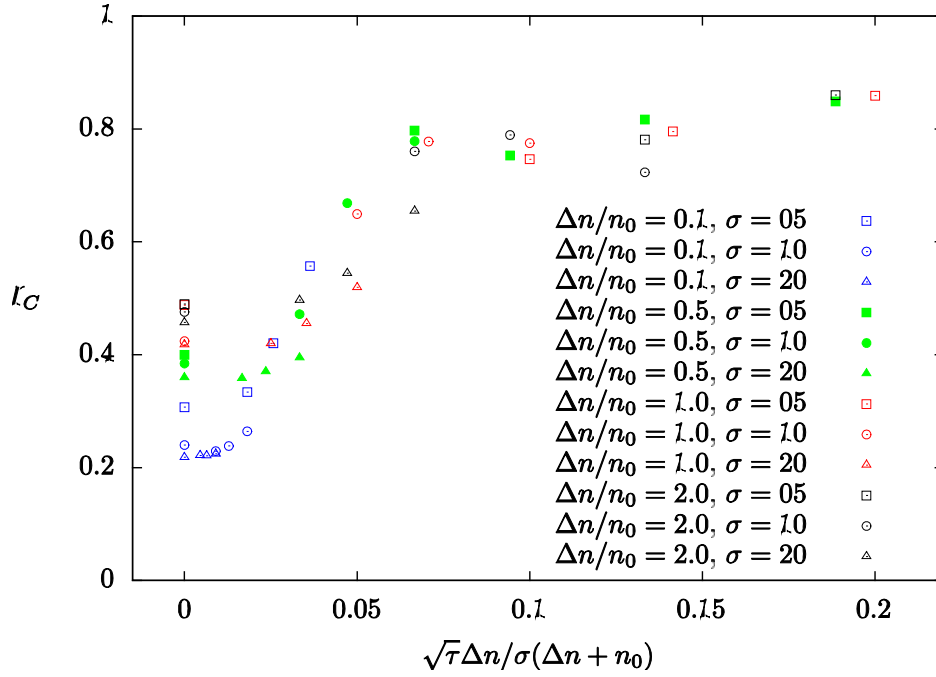


Figure 11. The particle density, l_C carried by the blob after 10 interchange times as a function of the ion gyroradius to the characteristic blob gradient length scale. τ denotes the ion to electron temperature ratio, σ denotes the blob width and Δn is the blob amplitude on top of the background level n_0 .

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2.2.12 Lagrangian invariants in gyrofluid model, turbulent equipartition and generalized potential vorticity equation.

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In a turbulent dominated system profiles of macroscopic quantities (e.g., particle density) are not necessarily formed by collisional diffusion. If adiabatic invariants mixed by the turbulent flow are sufficiently long lived the system can enter a state where the adiabatic invariants are spatially homogenised, and thereby determine the time-averaged profiles rather than collisional diffusion [1]. Up-gradient pinches are predicted in such turbulent equipartition (TEP) states [2]. The analysis is based on the identification and the turbulent mixing of Lagrangian invariants in the limit of no collisions.

In this work we extend previous investigations by including finite Larmor radius effects. The key observation is that the potential vorticity equation [3] when naively evaluated in the low-frequency limit possesses an approximate Lagrangian invariant namely the sum of the ExB and the ion diamagnetic vorticity. This approximate invariant gives a coupling between the ion pressure profile and the radial electric field. We have pursued this idea using a global gyrofluid model [4], mainly in order to circumvent the troublesome gyro-viscous tensor.

We have succeeded identifying four Lagrangian invariants in a four field gyrofluid model, and we have identified the associated TEP states. Furthermore, we are investigating how these results relate to the ion potential vorticity equation.

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2.2.13 Low-Dimensional Predator-Prey L-H Transition Model

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The confinement of particles and energy and thereby the performance of a fusion reactor is strongly influenced by turbulent transport. The L- and H-modes are confinement states of a toroidal plasma, referring to states of low and high confinement, respectively. In the L-mode the transport is generally increasing when the input power is increased until the edge heat flux exceeds a threshold value, where a transport barrier forms at the edge of the plasma and the plasma state enters the H-mode. The transition from the L- to the H-mode is called the L-H transition and it is observed by spontaneously improved confinement properties of the plasma. During the L-H transition the fusion plasma enters an intermediate mode characterized by oscillatory behavior. This oscillating mode is also called the transient mode or the T-mode.

Despite thorough investigations of the L-H transition it still lacks a first principle explanation. Significant insight into the L-H transition dynamics has been gained from models of the predator-prey type. In these models the zonal flow is the predator and the turbulence the prey. In the transient T-mode a cyclic interaction appears with oscillating turbulence intensity and zonal flow shear. These predator-prey type models are in the simplest form 0-dimensional in space, i.e., coupled first order ordinary differential equations. Kim and Diamond [1] suggested such a paradigm model for the development of the turbulence intensity, the zonal flow shear and the ion pressure gradient.

We have analyzed in detail the 3-ODE L-H transition model proposed by Kim and Diamond [1]. We provided a systematic study of the structural changes of the bifurcation diagram as a function of the remaining five parameters in the system. The findings from the bifurcation analysis were used to show that the model allows three types of transitions: an oscillating transition, a sharp transition with hysteresis and a smooth transition. Finally, we applied geometric singular perturbation theory to reduce the 3-ODE system to a 2-ODE system that contains all the same dynamics [2]. This showed that a 2-ODE system is sufficient for obtaining a minimal model of the L-H transition. An example of a solution to the reduced 2-ODE system is shown in Figure 12. The solution passes through the three different regimes: L-mode, T-mode and H-mode.

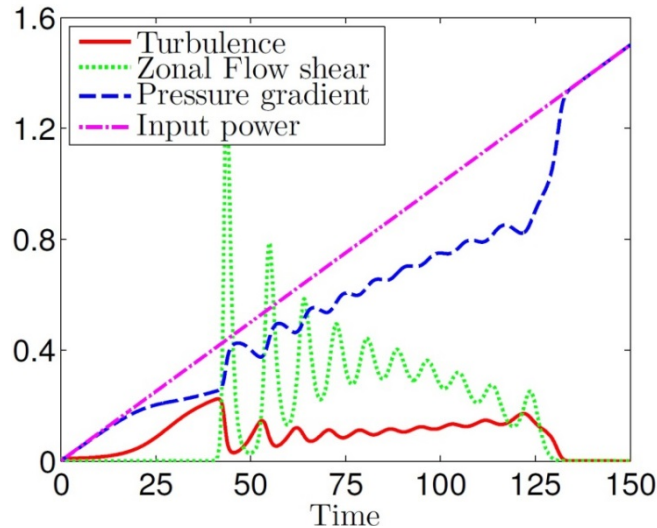


Figure 12. Numerical solution of the reduced 2-ODE predator-prey system. The temporal evolution of the turbulent intensity, the zonal flow shear, and the pressure gradient is shown for steadily increasing input power.

Miki et al. [3] have suggested a 1-spatial dimension 5-PDE predator-prey L-H transition model. The model takes the equations for the turbulence level and the zonal flow from the 3-ODE model by Kim and Diamond [1]. However, the growth rate and mean flow suppression of the turbulence now depends complexly on the spatial profiles of the three remaining dependent variables: the pressure, the density, and the poloidal mass flow. We have computed numerical solutions of this model and have initiated an investigation of the model structure.

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2.2.14 The distinction between type-III ELM and dithering cycles

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We have investigated the dynamics of type-III ELMs and particularly their distinction from the so-called dithering mode often observed in the transition from low confinement (L-mode) to high confinement (H-mode) in magnetically confined plasmas. The experiments are performed in the Experimental Advanced Superconducting Tokamak, (EAST) by applying a Langmuir-magnetic probe array. We observed that type-III ELMs, which occur near the power threshold for L-H transition, can be distinguished from the dithering cycles by the occurrence of precursor oscillations. This distinction was first noticed in ASDEX [1] and has now been further confirmed in EAST.

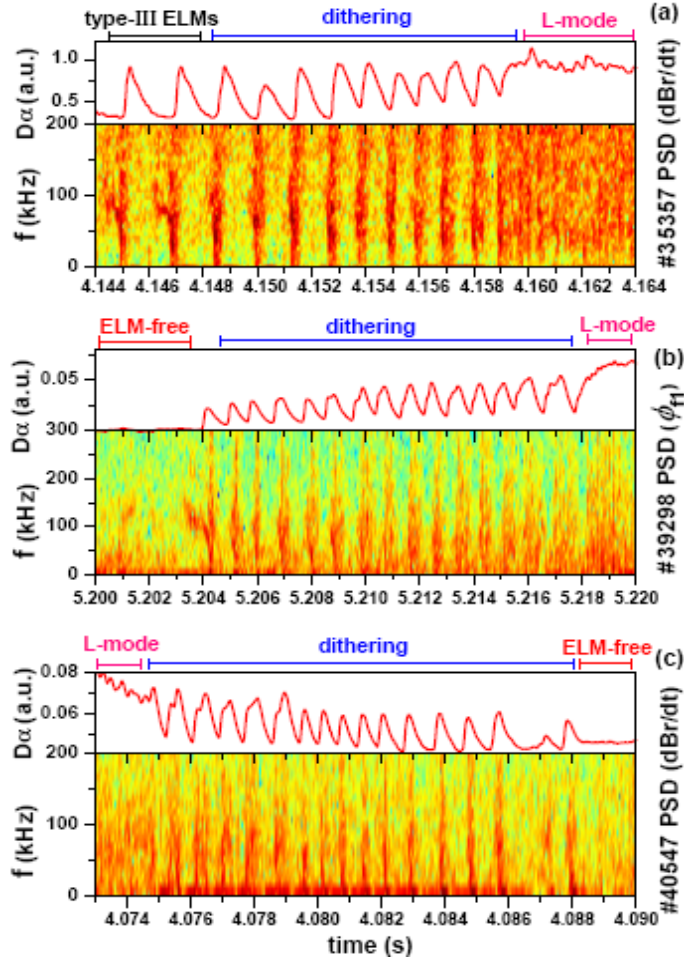


Figure 13. Divertor D_α emission together with power spectrum of various signals. (a) Magnetic fluctuations, dB_r/dt , during H-L transition. (b) Floating potential, ϕ_{f1} , during H-L transition. (c) Magnetic fluctuations, dB_r/dt , during L-H transition

In Figure 13(a), precursor oscillations with chirping frequency (130kHz-30kHz) are clearly observed before every type-III ELM event, but suddenly disappear for several ELM-like bursts, when the plasma is approaching the H-L back-transition. The H-L dithering cycles preceding this back-transition are thus highly likely to be the real perpetrator for the absence of the precursor mode. In Figure 13(b), the absence of precursor modes before the dithering cycles at H-L back transition is further confirmed by probing the floating potential evolution 1 cm inside the separatrix, here the precursor only appears prior to the first burst event at the transition from ELM-free H-mode to L-mode. The dithering at the L-H transition has been investigated also with magnetic probes near the separatrix (see Figure 13(c)). The precursor oscillations disappear in the dithering phase at the L-H transition as well. Thus, it seems that the precursor oscillation is a good signature to distinguish type-III ELMs and dithering cycles on EAST. Our observations are well consistent with the criterion for the distinction between type-III ELMs and dithering cycles drawn from the experiment in the ASDEX [1].

[1] H. Zohm. *et al.*, Nucl. Fusion **32** 489 (1992).

2.2.15 Observation of dithering H-mode in the SOL plasma on EAST

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The dithering H-mode is proposed as an intermediate phase (I-phase) between the L and H modes due to the hysteresis of the H-mode power [1]. The understanding of the dithering phenomenon may provide key insights for the mechanism of the L-H transition itself.

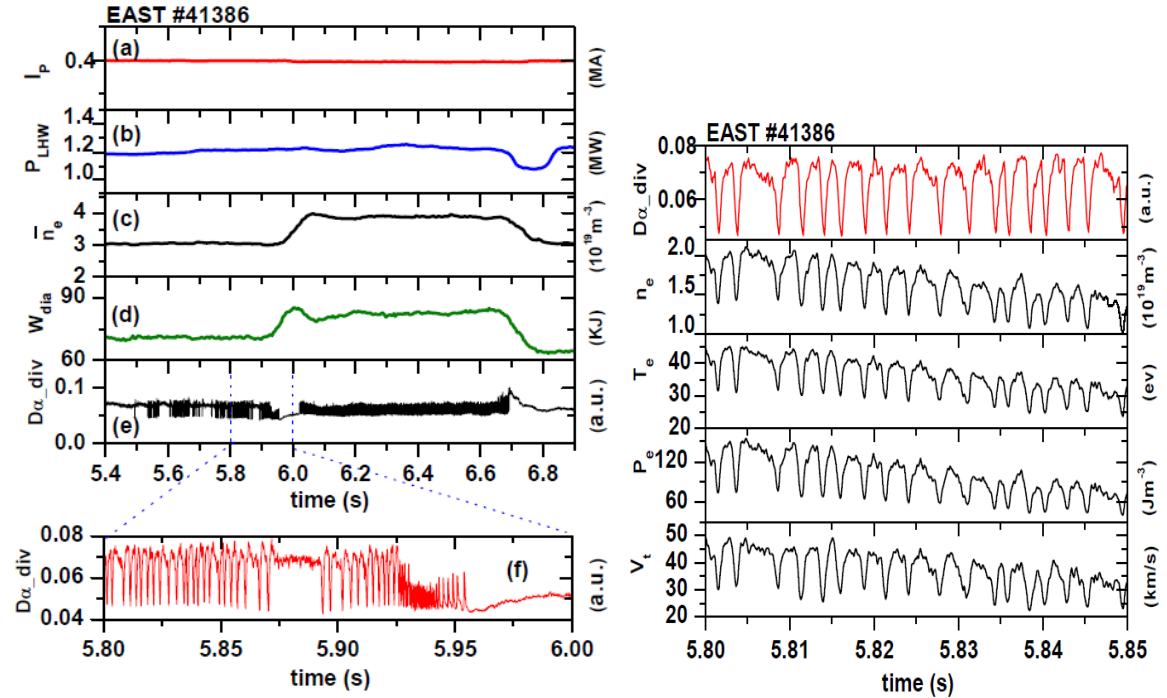


Figure 14. Left panel: The discharge parameters for #41386 on EAST (a) plasma current, (b) lower hybrid wave input power, (c) line-averaged density, (d) plasma stored energy, (e) divertor D_α emission, and (f) zoom-in plot of dithering H-mode in (e). Right panel: Langmuir-Mach probe measurement of SOL plasma parameter during dithering H-mode, plasma density n_e , plasma temperature T_e , plasma pressure P_e , toroidal velocity V_t .

In the vicinity of the power threshold for L-H transition, the plasma is observed to undergo a dithering H-mode on EAST. As shown in the left panel of Figure 14, the divertor D_α emission show a sequence of transient drops and jumps before the plasma eventually enter into a stable H-mode at 5.96 s. As indicated by the line-averaged plasma density and stored energy, it seems that the dithering H-mode do not enhance the confinement significantly as in a regular H-mode transition.

To characterize the dithering H-mode, Langmuir-Mach probe measurements are made in the near SOL region on EAST. It is found that the plasma density, temperature and pressure in the SOL drop simultaneously with the divertor D_α , which indicate a suppression of edge transport during these transient dithering H-modes states. The toroidal rotation of SOL plasma also decreases in the dithering H-mode. It could be attributed to the reduction on population of energetic ions in SOL. From 5.8 s to 5.85s, the plasma is kept in a dithering phase, where the

discharge remains stable, here the probes are located still near the separatrix. However, the SOL parameters are gradually reduced, with the extending of the dithering time during the measurements. The observations show that the dithering phase indeed regulates the edge transport and incrementally cooling down the SOL.

[1] F Wagner, Plasma Phys. Control. Fusion **49** B1-B33 (2007).

2.2.16 A mixed SOC-turbulence model for non-local transport and Lévy-fractional Fokker-Planck equation

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The cross field transport in magnetically confined plasmas is often found to be non-local in the sense that it is not solely depending on the local gradients of the transported thermodynamically variable. That is the standard Fick's law for diffusive transport cannot describe the experimental observations. This has clearly been revealed in the perturbative transport experiments [1 - 3], notably in the cold pulse experiments where a cooling at the plasma edge is observed to reach the plasma center on a time scale significantly shorter than a typical diffusive time scale, and in particular cases even leads to an increased temperature at the center [4,5].

We are investigating the phenomena of non-local transport in magnetically confined plasma theoretically. A hybrid model is proposed, which brings together the notion of inverse energy cascade, typical of drift-wave- and two-dimensional fluid turbulence, and the ideas of avalanching behavior, associable with self-organized critical (SOC) dynamics [6]. By applying statistical arguments, it is shown that an amplification mechanism is needed to introduce non-locality into the dynamics. We obtain a consistent derivation of non-local Fokker-Planck equation with space-fractional derivatives from a stochastic Markov process with the transition probabilities defined in reciprocal space. The hybrid model observes the Sparre Andersen universality and defines a new universality class of SOC. It will be applied to non-local transport phenomena in magnetized plasma.

[1] P. Mantica and F. Ryter, C. R. Physique 7, 634 (2006).

[2] V. Naulin, J. Juul Rasmussen, P. Mantica, D. del-Castillo-Negrete, and JET-EFDA contributors. J. Plasma Fusion Res. Series 8, 55 (2009).

[3] D. del-Castillo-Negrete, P. Mantica, V. Naulin, J. Juul Rasmussen, and JET EFDA contributors, Nucl. Fusion 48, 075009 (2008).

[4] K.W. Gentle et al., Phys. Rev. Lett. 74, 3620, (1995).

[5] P. Mantica, A. Thyagaraja, J. Weiland, G.M.D. Hogeweij, and P.J. Knight, Phys. Rev. Lett. 95, 185002 (2005).

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2.2.17 Gas puff modulation experiments in JET L- and H-mode plasma

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New JET experiments utilising gas puff modulation techniques [1-4] have been carried out in both L- and H-mode plasmas to study particle sources and transport both in the plasma core and in the pedestal region. The electron density response to the gas puff modulation was measured at 10 kHz sampling rate using a recently upgraded multi-band reflectometry [5] capable of measuring full radial profiles extending well across the separatrix down to densities $\sim 2 \times 10^{17} \text{ m}^{-3}$. In the L-mode session a 3-point dimensionless collisionality scan was performed. A simple analysis valid for a source free region is consistent with the earlier experimental database studies on JET [6] showing virtually no collisionality dependence. Gyro-kinetic quasi-linear analysis by QuaLiKiz confirms the results from the scan. However, it should be noted that weak collisionality dependence is found with QuaLiKiz when using artificial parameters nulling the small Te/Ti changes in the experimental scan. The first proof-of-principle H-mode gas modulation session in JET proved highly successful showing clear modulation (1-2% in the core) in electron density, see Figure 15. Various gas injection locations and frequencies were tested and the strongest electron density modulation for a given gas rate was obtained with an outboard midplane injection, with a modulation that is a factor of 1.5-3 larger than the one obtained with injection from the top or from the divertor. Since the SOL width is narrowest at the midplane this would seem to indicate that the direct fuelling (or “convection assisted direct fuelling”) could be responsible for a significant part of the total fuelling also in JET H-mode plasmas. This is quite interesting as the common understanding is that most of the fuelling is expected to be due to recycling especially in the X-point region.

*F. Romanelli et al. Fusion Energy 2012 (Proc. 24 IAEA Conf., San Diego, 2012) IAEA Vienna.

[1] K.W. Gentle et al. Nucl. Fusion **32**, 217 (1992)

[2] J O'Rourke et al. Plasma Phys. Contr. Fusion **35**, 585 (1993)

[3] K. Nagashima et al. Nucl. Fusion **33** 1677 (1993)

[4] D.R. Baker et al. Nucl. Fusion **38** 485 (1998)

[5] A. Sirinelli et al. Rev. Sci. Instrum. **81** 10D939 (2010)

[6] H. Weisen et al. Nucl. Fusion **45**, L1 (2005)

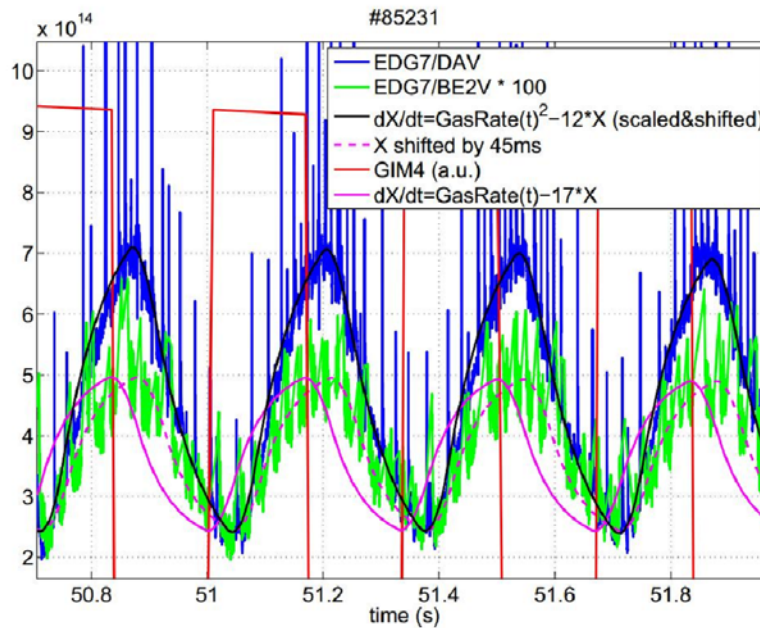


Figure 15. Photon fluxes as measured and gas rates indicating successful modulation of the local density in JET shot 85231. Modulation of gas inlet from GIM 4.

2.2.18 Participation in JET studies for confinement optimisation

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Mikhail Gryaznevich participated in P13-04, “Exploration of Beta limits with the ILW using RFA” as co-SC and in M13-09, “Extend hybrid performance by q-profile optimization and impurity control”. In these experiments, $n=1$ magnetic field perturbations were induced using 300 A current in EFCC coils, with a dynamic rotation of the perturbation at 30Hz. Resonant Field Amplification was measured to indicate the vicinity to the no-wall beta limit and the correlation between RFA data and 3D plasma deformation has been observed, see Figure 16. These experiments were cut short by the JET downtime and will be continued in 2014.

Furthermore we participated in preparations to M13-44 experiment, “3D equilibrium and fast ion confinement studies”. Within the scope of this programme, Mikhail participated in corresponding experiments on 3D equilibrium and fast ion induced TAE modes on COMPASS at IPP Prague, between the 11th and 15th November 2013. Some of results have been presented at IAEA TM on RUSFD, January 2014 and the ITPA Meeting on FP, in April 2014. A publication is in preparation.

[1] D. Yadykin, M. Gryaznevich, L. Frasinetti, S. Gerasimov and JET-EFDA Contributors. Effect of the external helical fields on the plasma boundary shape in JET. Nucl. Fusion 54 (2014) 013016

[2] M. Gryaznevich, A. Nicolai and P. Buxton. Fast particles in a steady-state compact FNS and compact ST reactor. Accepted for publication in Nuclear Fusion. A paper submitted to the IOP Open Access Journal of Physics Conference Series, as Proceedings of the 21st IAEA TM on RUSFD and LAWPP.

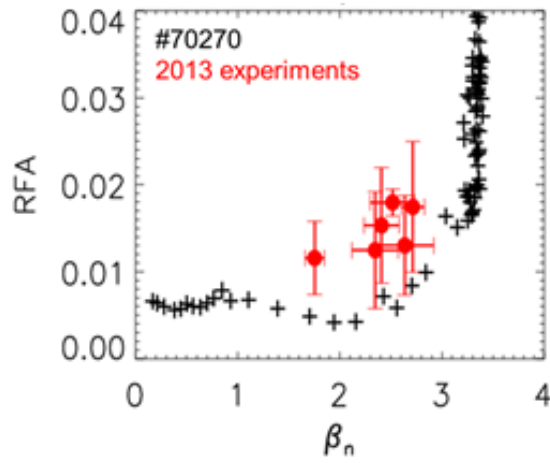


Figure 16 Resonant field amplification as function of β_n , showing the vicinity of the stability limit approached as β_n increases.

2.3 Diagnosing fusion plasmas by millimetre wave collective Thomson scattering

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Millimetre waves, corresponding to frequencies in the 100 GHz range, are used extensively in fusion research both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally.

At DTU, the millimetre wave collective Thomson scattering (CTS) diagnostic is developed and exploited with two diagnostic aims: for measuring the velocity distribution of confined energetic ions and for measuring the isotope composition (the so-called fuel ion ratio in a D-T fusion reactor) in fusion plasmas. The measurements are spatially localized with a resolution on the centimetre scale and have a temporal resolution on the millisecond scale.

The most energetic ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS). The importance of the fast-ion CTS diagnostic was further underlined by the fact that in 2008 the front-end of a fast ion CTS diagnostic system was enabled in the new ITER baseline design. In 2009 the updated ITER Baseline Design was finally approved by the ITER Council. DTU has developed the feasibility study and preliminary design of the ITER CTS diagnostic under EFDA task agreements. The work on CTS at ASDEX Upgrade and formerly TEXTOR should be seen in the context of maturing the diagnostic for future use on ITER.

In addition to the use of CTS to diagnose fast ions, the diagnostic technique may also be used to measure the fuel ion ratio in a fusion plasma – both temporally and spatially resolved. This can be done by choosing particular scattering geometries and measure the effect of ion Bernstein waves and ion cyclotron motion on the CTS spectrum. This novel use of CTS is welcomed by the community since the measurement of the fuel ion ratio in ITER is a challenge with the current diagnostic set.

The group has developed and implemented a CTS diagnostic system at the ASDEX Upgrade tokamak, which is located at the Max-Planck Institute for Plasma Physics in Garching, Germany. In the last year, a new milestone for CTS has been reached at ASDEX Upgrade where a novel background subtraction technique has paved the way for a reliable evaluation of the scattering spectra. The dynamics of both the bulk- and fast-ions can now be diagnosed and examples of such activities on ASDEX Upgrade are described in sections 2.3.2 - 2.3.7.

The original CTS receiver, previously installed in the gyrotron hall, has been upgraded and moved to the CTS diagnostic room. The proximity of the two receiver systems adds synergy, reduces the system complexity and adds flexibility with respects to coupling to the transmission lines. The reallocation and upgrading of the receiver system are discussed in sections 2.3.9 - 2.3.11.

Work on integrating experimental information from several fast ion diagnostics has been performed. The results of these efforts are given in section 2.3.8.

The involvement in the JET 2013 work program is summarized in sections 2.3.12. Finally, activities related to obtain a F4E FPA are summarized in section 2.3.13.

2.3.1 EFDA tasks in 2013 for the DTU CTS group

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During 2013, the CTS group has participated in the following EFDA tasks:

- **WP13-IPH-A09-P2-02:** Diagnosing Fast Ion Behaviour in ITER and ASDEX upgrade. The contributions are described in Secs.2.3.2 - 2.3.5 and 2.3.7 - 2.3.8.
- **WP13-IPH-A10-P1-01:** Comprehensive investigation of fuelling and pumping operation properties of tokamaks. The contributions are described in 2.3.6.

2.3.2 New CTS setup at ASDEX Upgrade - Dual receiver technique

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Collective Thomson scattering (CTS) can provide measurements of the confined fast-ion distribution function resolved in space, time and 1D velocity space. On ASDEX Upgrade, the measured spectra consist of a CTS contribution, which is generated in the scattering volume where the probe and receiver beams cross, a background ECE contribution and a contribution which is currently not understood. The latter is believed to be generated by interaction between the probe beam and the plasma elsewhere.

A new set-up using two independent heterodyne receiver systems enables subtraction of the unknown part from the total spectrum, revealing the resulting CTS spectrum. This has been demonstrated in 2013 where the two CTS receivers at ASDEX Upgrade have been operated in parallel. The results are achieved by using a new technique to eliminate the spurious part of the CTS signal using two receiver systems operated as an active and a passive view, respectively. The setup is illustrated in Figure 17.

The scattering radiation generated in the scattering volume, defined as the overlap between the active view and the probe beam, is collected by the active receiver. The passive view has no overlap with the probe beam. The spurious signal is not generated in the CTS scattering volume and has only a weak dependence of the viewing direction.

In Figure 18 time traces for two channels with similar frequency coverage in the active and the passive view are shown during an L-mode overlap sweep. No energetic ions are injected or generated in this part of the discharge. In the beginning of the sweep the evolution of the spectral power density in both receivers is very similar both during the periods with the gyrotron switch on and off. At around $t=2.25$ s the active receiver view is expected to cross the gyrotron beam. We note that the difference between the gyrotron on and off periods is enhanced in the active receiver channel (Figure 18a) at around $t = 2.25$ s while no significant difference is observed in the passive receiver (Figure 18c). This illustrates that the CTS spectrum can be extracted. The obtained CTS spectra are in general in agreement with theoretical expectations.

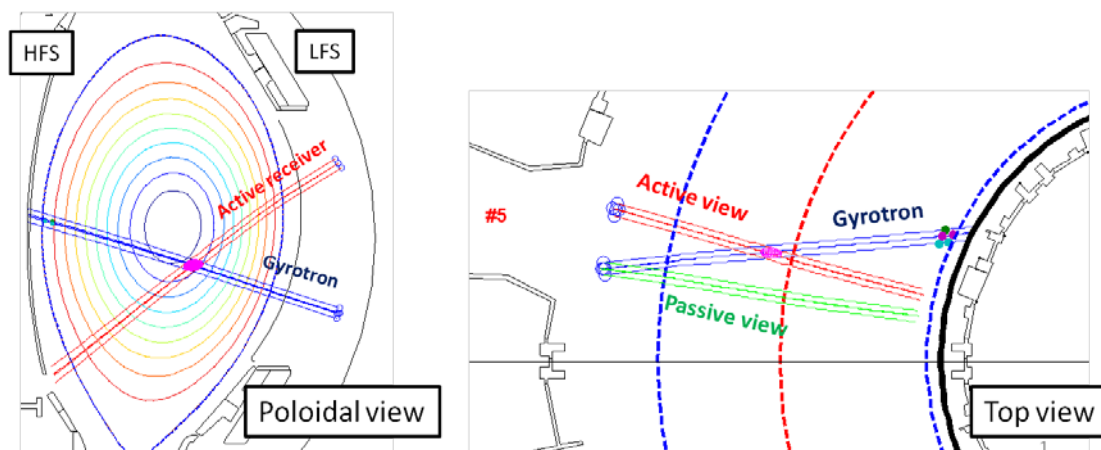


Figure 17 schematic of the scattering geometry for CTS setup at ASDEX Upgrade.

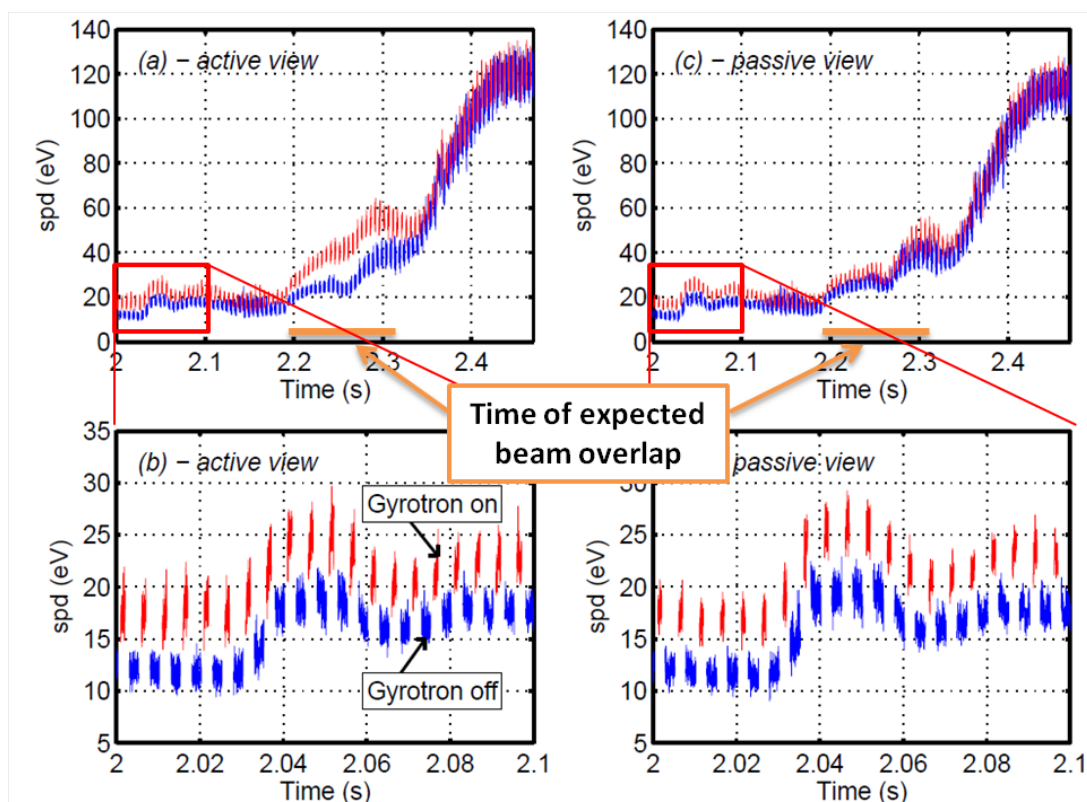


Figure 18: Time traces of raw CTS signal in the active and passive receivers during overlap sweep. Background is shown in blue and the signal during gyrotron probing time is shown in red. A clear difference in the signal levels in between the passive and active views is seen at the time of beam overlap at 2.25 s

2.3.3 Improved Collective Thomson Scattering measurements of fast ions at ASDEX Upgrade

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A key outcome of CTS measurements is the characterization of 1D fast-ion velocity distributions $g(u)$ in the plasma. However, earlier CTS results obtained at ASDEX Upgrade (AUG) have shown some quantitative discrepancies between the inferred $g(u)$ and predictions by numerical simulations [1, 2]. This was plausibly related to the presence of “spurious” emission in measured CTS spectra which could not be adequately subtracted. The new dual-receiver CTS setup [3] has enabled improved subtraction of the background signal, and hence the first accurate characterization of fast-ion properties at AUG [4]. For the first time, this has enabled us to clearly observe the expected broadening of the CTS spectra with increasing NBI heating energy, see Figure 19. Comparison of the underlying 1D fast-ion velocity distribution, as inferred from the resulting CTS spectra, with numerical predictions from the transport code TRANSP also reveals the first convincing agreement between theory and AUG CTS measurements of fast ions (Figure 20). These results demonstrate that quantitative CTS studies of fast-ion dynamics at AUG are now feasible.

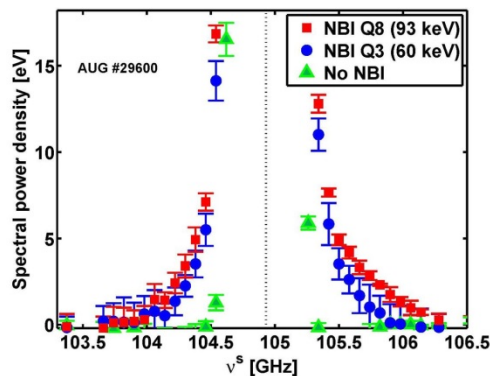


Figure 19. Comparison of CTS spectra obtained in AUG discharge 29600 during phases with and without one-beam NBI heating. The CTS data have been averaged over 10 gyrotron pulses. Dotted line marks the frequency of the probing gyrotron beam

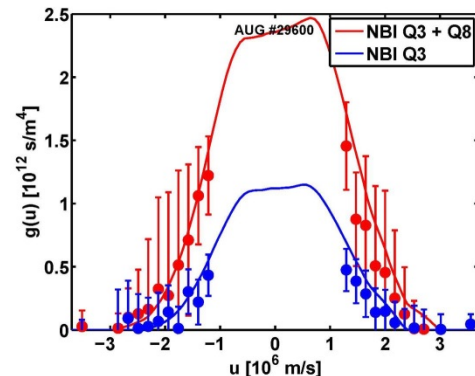


Figure 20. Fast-ion velocity distributions obtained from CTS data in discharge 29600 during one- and two-beam NBI heating (data points), compared to the corresponding predictions from TRANSP simulations (solid lines).

- [1] F. Meo, M. Stejner, M. Salewski, *et al.* Journal of Physics: Conference Series **227**, 012010 (2010)
- [2] M. Salewski, F. Meo, M. Stejner, *et al.* Nuclear Fusion **50**(3), 035012 (2010)
- [3] S. K. Nielsen, M. Stejner, J. Rasmussen, *et al.* submitted to Nuclear Fusion (2014)
- [4] J. Rasmussen, S. K. Nielsen, M. Stejner, *et al.* to appear in AIP Conf. Proc. "Fusion Reactor Diagnostics", eds. F. P. Orsitto *et al.* (2014), <http://arxiv.org/abs/1310.2406>

2.3.4 Comparing real and synthetic fast-ion measurements at ASDEX Upgrade

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Accurate and internally consistent characterization of fast-ion properties from multiple diagnostics is a crucial prerequisite for forthcoming attempts to perform multi-diagnostic velocity-space tomography of fast ions. While the output of different fast-ion diagnostics cannot be directly compared, they can each be contrasted with the same numerical simulation in order to gauge their internal consistency. To this end, we are comparing fast-ion properties inferred with both the CTS, FIDA, and neutron rate detectors at ASDEX Upgrade to numerical predictions from the TRANSP [1] transport code. Explicit account of uncertainties in the TRANSP predictions is being made on the basis of estimated uncertainties on relevant plasma parameters. Preliminary results from AUG discharge 29600 indicate that these three diagnostics all show reasonable agreement with theory within the errors (Figure 21). This paves the way for detailed tomographic reconstructions of the 2D fast-ion distribution function using multiple fast-ion diagnostics.

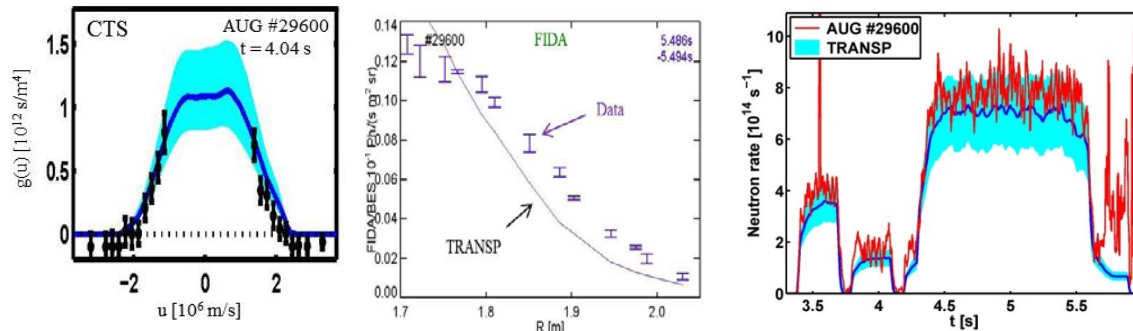


Figure 21. Example comparison of real and synthetic fast-ion measurements from CTS, FIDA, and neutron rate diagnostics in discharge 29600 at ASDEX Upgrade. Left: 1D fast-ion velocity distribution derived from CTS, compared to TRANSP predictions (solid line) and their uncertainties (filled). Centre: Measured and predicted radial FIDA intensity profiles. Right: Measured neutron rates (red), along with TRANSP predictions colour coded as in the left plot.

[1] A. Pankin, D. McCune, R. Andre, *et al.* Comp. Phys. Comm. **159**, 157 (2004)

2.3.5 Upgrading the fast acquisition system for FFT-based CTS measurements on AUG

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The CTS system at AUG includes a fast acquisition system [1], which allows direct digitization of the CTS signal at rates up to 12.5×10^9 Samples/s (12.5 GS/s). Finely resolved spectral information with frequency resolutions in the MHz range can then be extracted through Fourier analysis of the measured signal. This setup is used for measurements of the bulk-ion region of CTS spectra and thereby enables access to information about the thermal ion populations in the plasma including such properties at the ion temperature, plasma rotation velocity and the

isotopic composition of the plasma. The fast acquisition system is illustrated in Figure 22 and an example of spectra measured with this system is shown in Figure 23.

The ADC used for this type of measurements is an NI PXIe 5186, which provides 8-bit resolution at sample rates up to 12.5 GS/s. The system is normally operated at 6.25 GS/s, and until now, the total acquisition time was then limited to 160 ms by the 1 GB on-board memory of the ADC. In order to alleviate this constraint the system was upgraded after the 2013 AUG campaign to include a new embedded controller unit: the NI PCIe-8135. This enables streaming of data from the ADC to the controllers memory at rates up to 800 MB/s during a plasma discharge, thus continuously freeing up the on-board memory of the ADC for new data. Test with the upgraded controller show that it will now be possible to acquire data sets of about 5 GB during a 7 s plasma discharge, corresponding to a total acquisition time of 0.8 s or a duty cycle of 11%, up from 2% with the previous setup. The additional acquisition time will be used to increase the signal-to-noise ratio of the CTS measurements and to provide coverage for a greater share of each discharge.

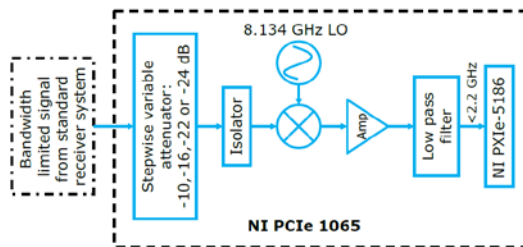


Figure 22. A bloc diagram illustrating the fast CTS acquisition system on AUG. Part of the signal from the standard receiver system is further down-converted using a mixer and a local oscillator and the down converted signal is fed to a fast ADC: the NI PXIe-5186 providing 8-bit resolution at a sample rate of 6.25 GS/s. The whole system is mounted in an NI PCIe-1065 chassis. The signal passed to the ADC is band pass limited and down converted such that it covers a roughly 2 GHz wide band centred on the CTS probing frequency at 105 GHz.

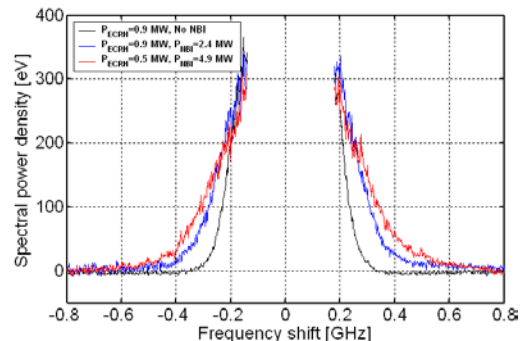


Figure 23. Examples of spectra measured in AUG discharge

29600 with different NBI powers: at $t = 2.38$ s with no NBI

(black), at $t = 2.10$ s with NBI source Q3 alone (blue) and at $t = 3.43$ s with Q3 and Q8 combined (red). The spectra are clearly seen to become wider at higher heating power. A small asymmetry in the spectra also indicates the presence of plasma rotation during phases with NBI heating

[1] M. Stejner, S. Nielsen, A. S. Jacobsen, S. B. Korsholm, F. Leipold, F. Meo, P. K. Michelsen, D. Moseev, J. Rasmussen, M. Salewski, M. Schubert, J. Stober, and D. H. Wagner, In preparation, to be submitted. to RSI.

2.3.6 First bulk ion measurements by CTS on AUG

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A new acquisition system was recently added to the CTS receiver at ASDEX Upgrade (AUG) to enable measurements with frequency resolution around 1 MHz and thereby access to the

information contained in the bulk ion region of the measured CTS spectra [1]. The required frequency resolution is achieved by means of direct digitization of the CTS signal using a fast digitizer, the NI PXIe-5186, providing 8-bit dynamic range with sampling rates up to 12.5 GS/s and an analogue bandwidth of 5 GHz. Spectral information is then extracted through Fourier analysis of the time-domain data after the plasma discharge permitting flexibility in the choice of time and frequency resolution.

In 2013 we have improved the calibration of this fast acquisition system and benchmarked it against the filter bank-based receiver system used for fast-ion CTS. In Figure 24 we show an example of the spectra obtained in a fast-ion CTS geometry with both receiver techniques. Good agreement between the two systems is found. This new FFT-based receiver system enables new physics exploration in terms of plasma composition measurements together with ion temperature and drift velocity measurement by CTS.

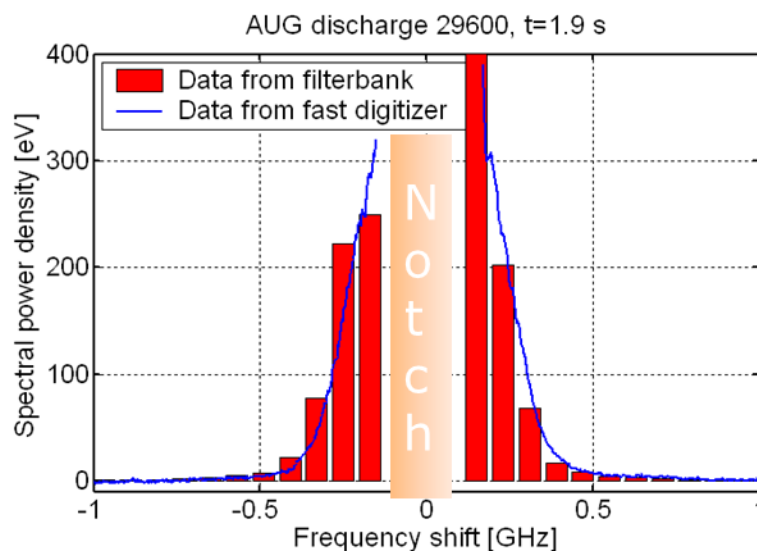


Figure 24. Comparison between CTS spectra obtained with FFT-based system (blue) and filterbank system (red).

Using the data from the FFT-based system, detailed information about the ion properties can be extracted from the spectra. In the fast-ion CTS geometries, the ion temperature and drift velocity can be estimated from fits to theoretical CTS spectra. Figure 25 shows an example of CTS measurements in an NBI heated discharge where the width of the measured CTS spectra is clearly seen to vary with the ion temperature.

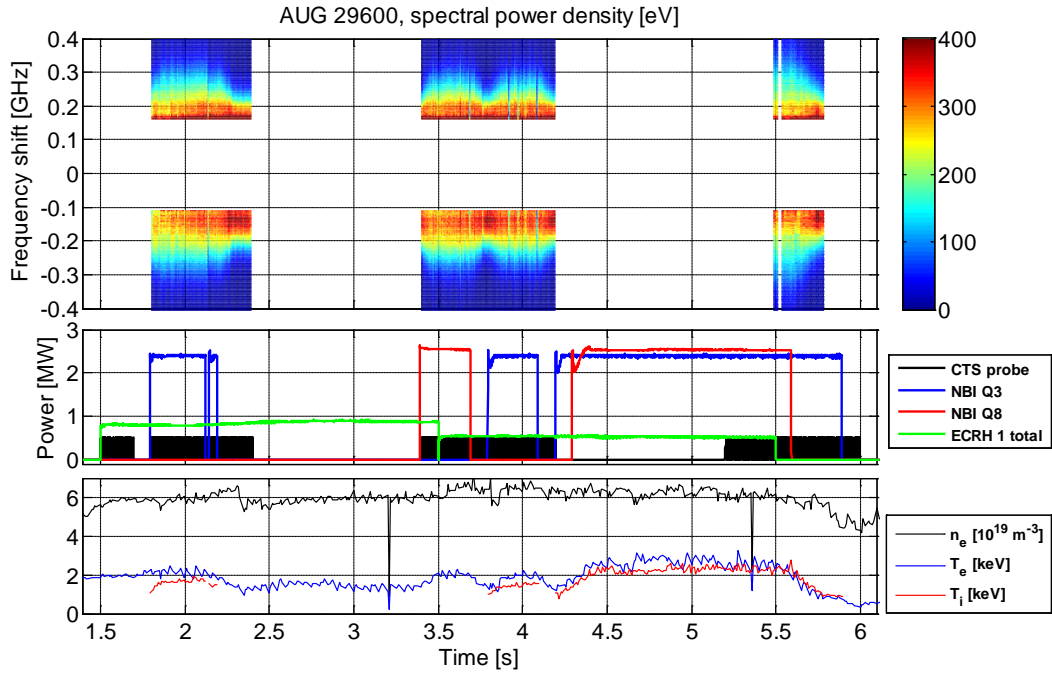


Figure 25. CTS measurements in AUG discharge 29600. The top panel shows a spectrogram of the bulk ion region of the CTS spectra measured with the FFT-based receiver setup. The middle panel shows time-traces for the NBI and ECRH heating systems as well as the CTS probing gyrotron. The lower panel shows electron temperatures and densities measured with non-collective Thomson scattering and ion temperatures measured with charge exchange recombination spectroscopy (which is only possible when NBI Q3 is on). The CTS spectra in the upper panel are seen to vary in width with the ion temperature, becoming broader when the NBI heating is turned on and the ion temperature consequently increases.

To interpret the measurements, the spectra are fitted with a theoretical model for CTS [2], as illustrated in Figure 26. The values of the ion temperature and drift velocity inferred from these fits are compared to similar measurements of the quantities from Charge eXchange Recombination Spectroscopy (CXRS) in the lower panel of Figure 26. Good agreement between the two diagnostics is found for both ion temperature and bulk ion rotation.

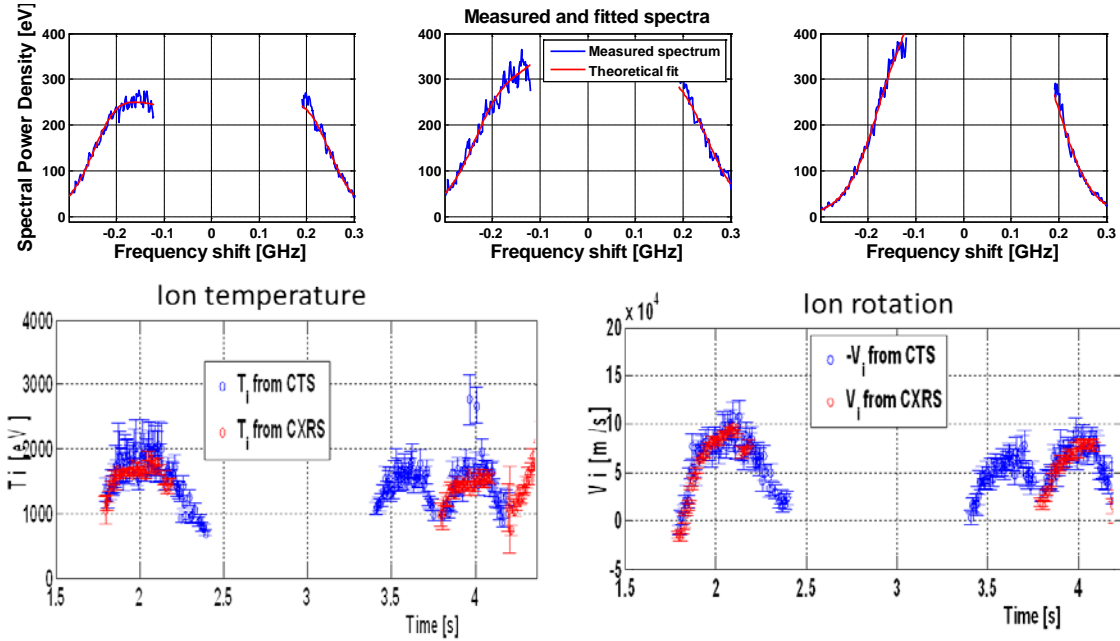


Figure 26. Upper panel: examples of measured and fitted bulk-ion CTS spectra from AUG discharge 29600. Lower panel: measurements of ion temperature (left) and ion drift velocity (right) by CTS (blue) and CXRS (red) in ASDEX discharge 29600. All measurements are performed at $p_T \sim 0.2$

Having the technique in place as described above, measurements of the isotope ratio was performed to demonstrate the diagnostic capability. In the experiments presented in this section, having a minority hydrogen concentration in a deuterium plasma, were conducted in discharge 29601. This technique relies on the ability to resolve the signatures on the ion cyclotron motion and of weakly damped ion Bernstein waves, which appear as peaks in the CTS spectrum at frequency intervals of 20-40 MHz when the resolved fluctuation wave vector is near perpendicular to the magnetic field [3]. Resolving these features in the CTS spectrum is thus only possible using the FFT-based receiver system. The peak separation depends on the ion-cyclotron frequency, the isotope ratio can be inferred from these features because the shape and relative height of peaks related to different ion species depend, among, other variables, on their relative densities. This is clearly seen in Figure 27 illustrating measurements in plasmas dominated by deuterium and hydrogen, respectively. It is clear that for the hydrogen dominated plasma the signatures/peaks are spaced about 40 MHz from each other while this distance is about 20 MHz for the deuterium discharge.

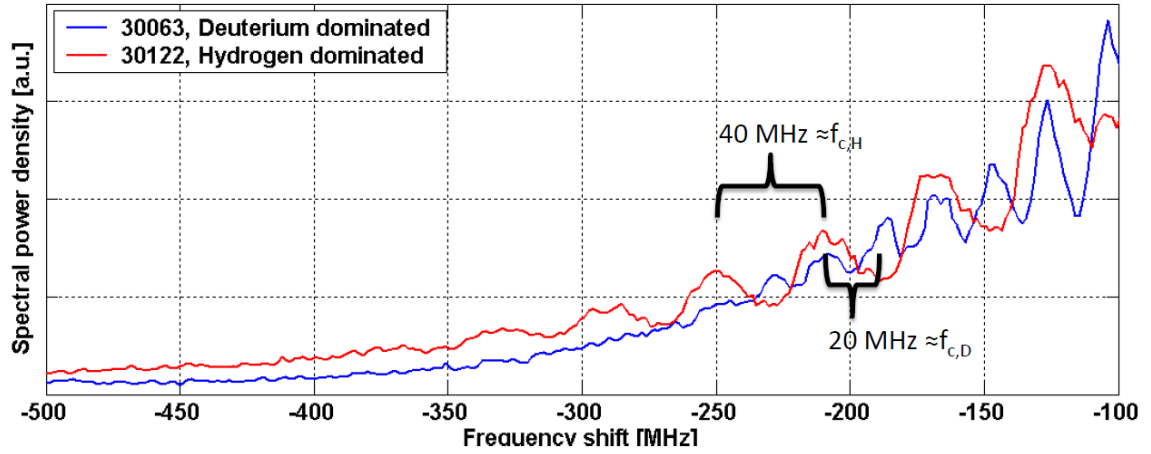


Figure 27. The down-shifted part of two CTS spectra showing signatures of the ion cyclotron motion and ion Bernstein waves. The signatures appear as peaks separated by frequency intervals corresponding to the ion cyclotron frequency of the dominant ion species – i.e. at intervals of roughly 20 MHz in discharge 30063, which was dominated by deuterium, and at intervals of 40 MHz in discharge 30122, which was hydrogen dominated.

To interpret the measurements, we fit the spectra with a theoretical model for CTS [2]. As illustrated in Figure 28, it is found that hydrogen concentrations in the order of 2-4 % can be determined.

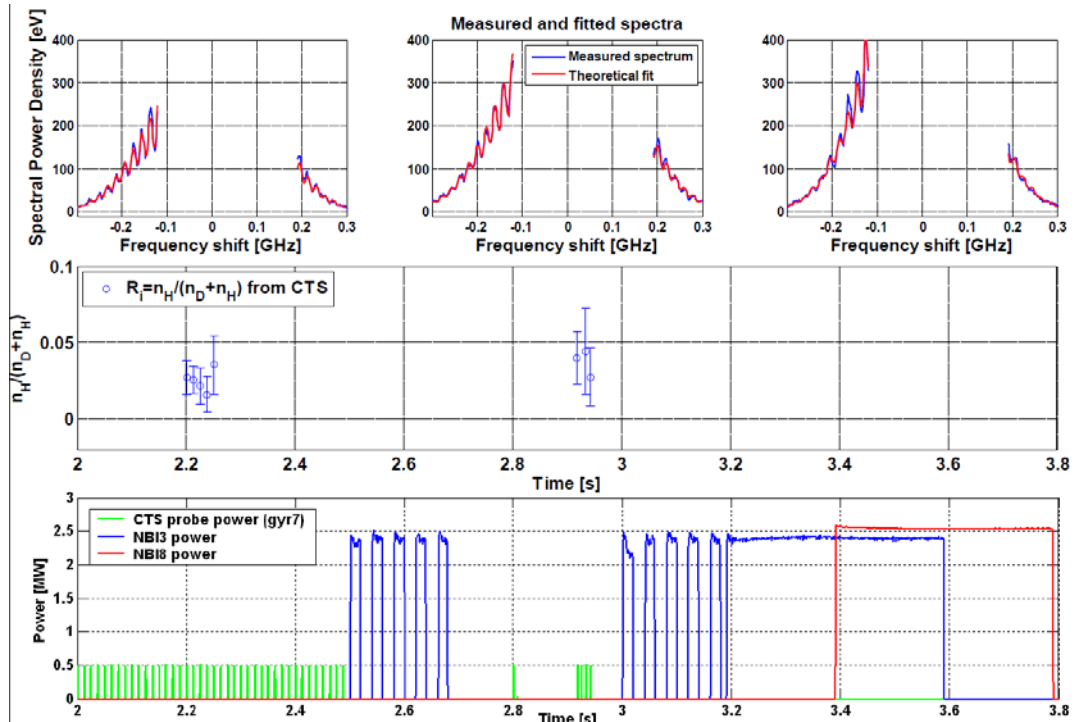


Figure 28. Measurements of the hydrogen concentration in a deuterium dominated plasma in ASDEX discharge 29601. All measurements are performed at $p_T \sim 0.2$. The upper panel shows examples of measured and fitted spectra, the middle panel shows the inferred isotope density ratios and the lower panel shows time traces for the NBI heating systems and the CTS probing gyrotron.

An experiment, illustrated in Figure 29, was also made in a hydrogen discharge, 30124, where residual helium from a preceding glow discharge is expected to significantly influence the plasma composition. For low frequency shifts from the probing source frequency an extra peak is seen, which can be expected to be from helium. However, one should also note that the cyclotron frequency of deuterium and helium are the same, so it could also be an effect of residual deuterium. However, there is also a mass dependence on the signatures, so that signatures of heavier ion species decay in amplitude faster (when displacing away from the probing frequency) than for lighter species. Since the 20 MHz signature is only present for small shifts from the probing frequency, one may conclude that it is a fair assumption to state that it is a signature from helium.

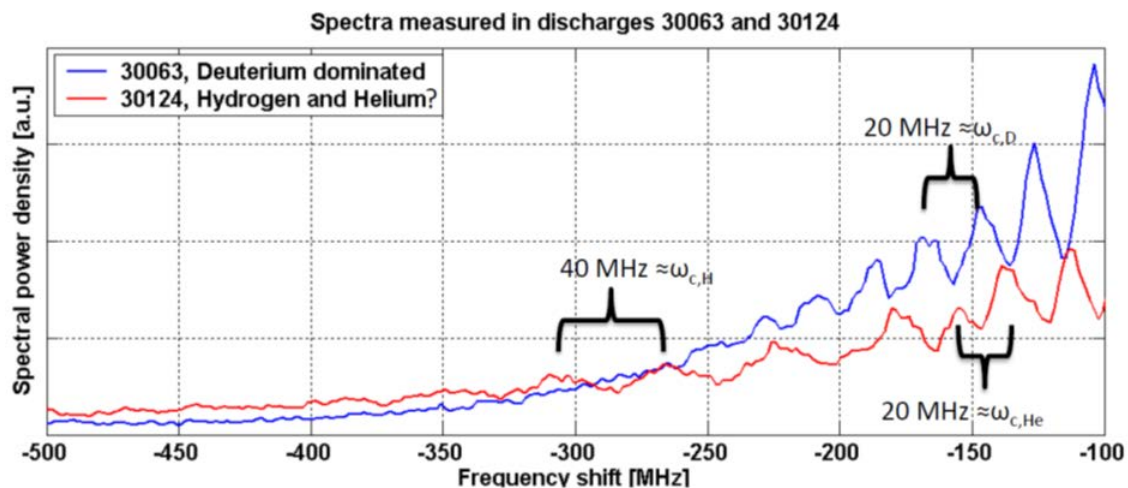


Figure 29. Comparison of spectra measured in a deuterium dominated discharge, 30063, and a hydrogen dominated discharge, 30124, where residual helium from a preceding glow discharge is expected to significantly influence the plasma composition. In that discharge peaks appear at frequency interval corresponding to helium at low frequency shifts and to hydrogen at larger frequency shifts.

- [1] M. Stejner, S. Nielsen, A. S. Jacobsen, S. B. Korsholm, F. Leipold, F. Meo, P. K. Michelsen, D. Moseev, J. Rasmussen, M. Salewski, M. Schubert, J. Stober, and D. H. Wagner, To Be Submitted. to RSI 1 (2014).
- [2] H. Bindslev, J. Atmos. Terr. Phys. **58**, 983 (1996).
- [3] M. Stejner, S. K. Nielsen, H. Bindslev, S. B. Korsholm, and M. Salewski, Plasma Phys. Control. Fusion **53**, 065020 (2011).

2.3.7 Experimental inference of a 2D fast-ion velocity distribution function from many-view FIDA measurements on ASDEX Upgrade

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We have performed the first-ever measurement of a local fast-ion 2D velocity distribution function $f(v_{\parallel}, v_{\perp})$. To this end, we heated a plasma in ASDEX Upgrade by neutral beam injection and measured spectra of fast-ion D-alpha (FIDA) light from the plasma center in three views simultaneously. The measured spectra agree very well with synthetic spectra calculated from a TRANSP/NUBEAM simulation. Based on the measured FIDA spectra alone, we infer $f(v_{\parallel}, v_{\perp})$ by tomographic inversion. Salient features of our measurement of $f(v_{\parallel}, v_{\perp})$ agree reasonably well with the simulation as Figure 30 illustrates: the measured as well as the simulated $f(v_{\parallel}, v_{\perp})$ are lopsided towards negative velocities parallel to the magnetic field, and they have similar shapes. Further, the peaks in the simulation of $f(v_{\parallel}, v_{\perp})$ at full and half injection energies of the neutral beam also appear in the measurement at similar velocity-space locations. We expect that we can measure spectra in up to seven views simultaneously in the next ASDEX Upgrade campaign for a combined CTS/FIDA measurement which would further improve measurements of $f(v_{\parallel}, v_{\perp})$ by tomographic inversion. A full account of the experimental demonstration of the velocity-space tomography approach is given in [1].

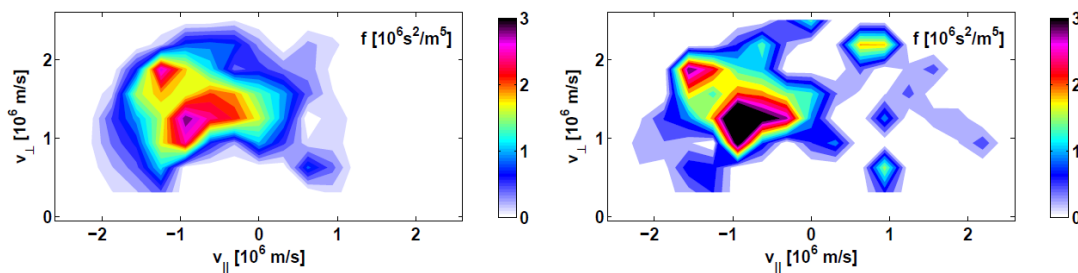


Figure 30. TRANSP distribution (left) and tomography from experimental data (right) for ASDEX Upgrade discharge 29578

[1] M. Salewski *et al.* Nucler Fusion **54** 023005 (2014).

2.3.8 Benefits of many-view CTS/FIDA diagnostics with up to 15 views

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We investigated what can be gained by installing additional FIDA or CTS views on ASDEX Upgrade. This year we have achieved an experimental inference of a fast-ion velocity distribution function using three simultaneous FIDA views [1]. Previously, we have investigated theoretical tomographies using up to four synthetic views [2,3]. Our investigations have already triggered the installment of 2 additional FIDA views available in the next ASDEX Upgrade

campaign. This would give a total of seven views since the five FIDA views could be combined with up to two CTS views in joint tomographies. Here we pushed the limits further and study up to twelve synthetic FIDA/CTS views and study the effect of noise. The use of synthetic diagnostics allows us to compare the tomography with the original 2D velocity distribution used to compute the synthetic measurements. Figure 31 - Figure 34 illustrates this comparison between the original and 3 example tomographic inversion using 4, 8, and 12 views and 5% noise added to the synthetic data. The reconstruction of locations and amplitudes of the beam injection peaks improves with the number of views. A full account is given in [4].

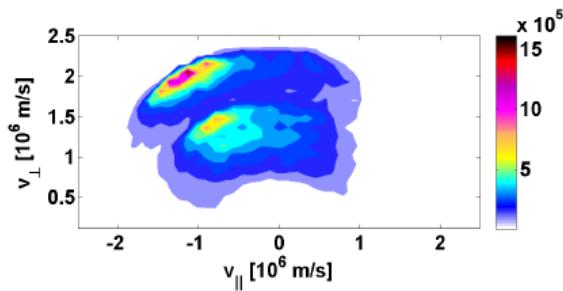


Figure 31: Original TRANSP simulation used to calculate synthetic CTS and FIDA diagnostic (NBI at ASDEX Upgrade).

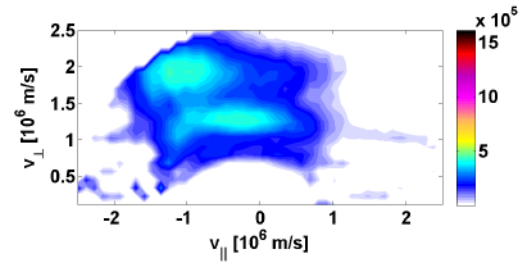


Figure 32: Tomography from synthetic measurements in 4 FIDA views with 5% noise

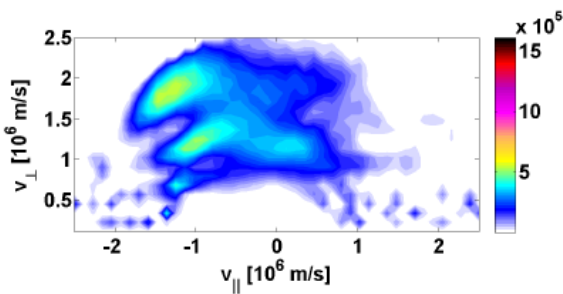


Figure 33: Tomography from synthetic measurements in 8 FIDA views with 5% noise

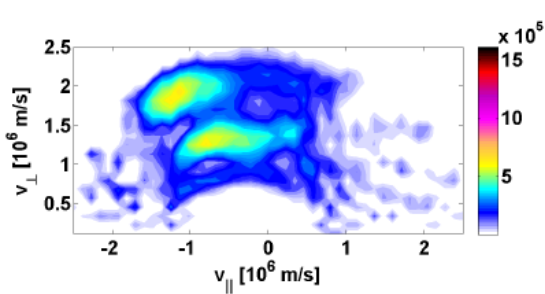


Figure 34: Tomography from synthetic measurements in 12 FIDA views with 5% noise

- [1] M. Salewski et al. Nucl. Fusion **54** 023005 (2014)
- [2] M. Salewski et al., Nucl. Fusion **52** 103008 (2012)
- [3] M. Salewski et al., Nucl. Fusion **53** 063019 (2013)
- [4] Jacobsen et al. EPS conference proceedings (2013)

2.3.9 In-vessel beam alignment

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Good beam alignment is essential for CTS operation at ASDEX Upgrade. In order to perform reliable ray tracing, the beam propagation in vacuum must be known with a certainty of less than a degree. The beam patterns of the ECRH transmission lines have been measured through by DTU and IPP in 2013 during the summer opening for a number of different mirror settings. The measurements were performed by inserting a 103 GHz source in the overmoded waveguides radiating towards the plasma and detecting the beam pattern using the DTU

constructed micro-rig. Once the centre of the centre beam was found, the 3D position was measured by the FARO arm with an uncertainty of less than 1 mm. An illustration of the alignment set-up is shown in Figure 35, and an example of the measured beam waist is shown in Figure 36. In general, good agreement was found between the theoretical beam pattern and the measured beam pattern was found. The beam width of the measured beam pattern was also compared to theoretical calculations and good agreement was found.



Figure 35. Photograph of alignment setup inside ASDEX Upgrade

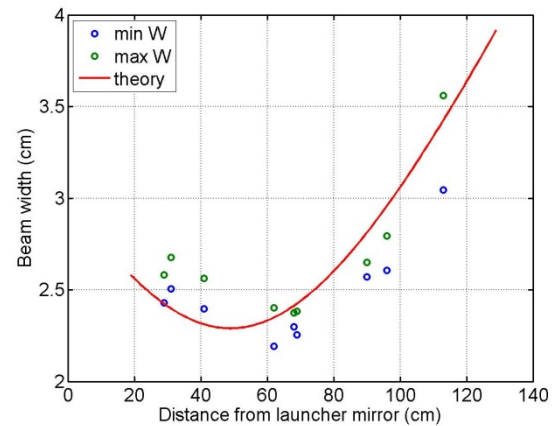


Figure 36. Measurements of beam waist vs. theoretical calculation for the transmission line of AUG gyrotron 7.

2.3.10 Movement of CTS receiver to diagnostic room

S. K. Nielsen, M. Jessen, J. Rasmussen, S. Nimb, M. Stejner, S.B. Korsholm, F. Leipold
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The original CTS receiver installed in the AUG ECRH2 gyrotron hall has been moved to the CTS diagnostic room to allow for more flexibility in designing the scattering geometries. In the new setup both the CTS receivers can easily be moved between different ECRH transmission lines and thus a number of new scattering geometries can now be realised. In order to facilitate easy coupling between the different transmission lines a compact optics unit has been constructed at DTU and installed at ASDEX Upgrade during 2014. The unit consists of a transparent polarizer unit, discussed in the next section, a flat movable mirror, used for calibration purposes, and a focusing mirror which matches the beam pattern to the oversized corrugated waveguide. The setup is shown in Figure 37. The rest of the receiver components have successfully been adapted to the setup and first test of the system show very good performance. Test on plasma discharges are being performed in early 2014.

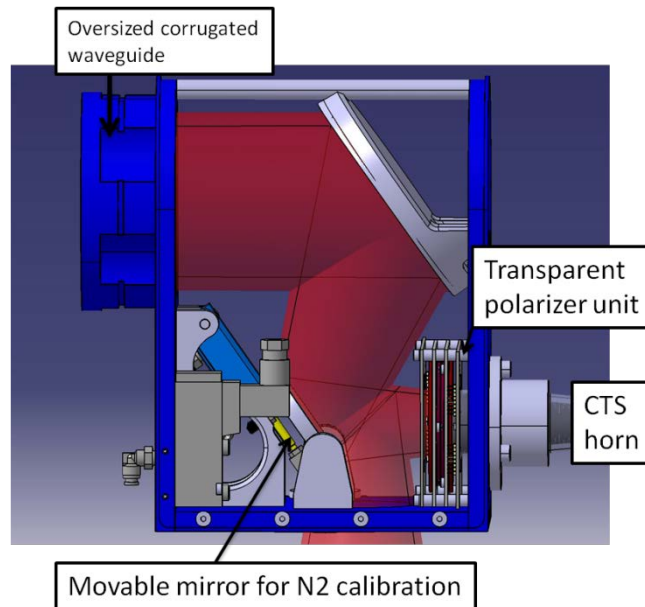


Figure 37. Technical CATIA drawing of new compact receiver optics unit.

2.3.11 Verification of the performance of the new compact CTS receiver

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The polarizers of the compact quasi-optics unit are adjusted before an experiment according to the polarization of the signal being expected. The settings of the polarizer are calculated using a simulation code. In order to verify the simulation code, a linearly polarized mm wave source was placed at the input of the receiver box and the polarization of the output was measured using a 2 channel heterodyne detector. The polarizers were rotated in steps of 15 degree. Measured and calculated polarization is plotted in Figure 38. Measurements and calculations are in good agreement. The model can be used in order to calculate the required polarizer setting.

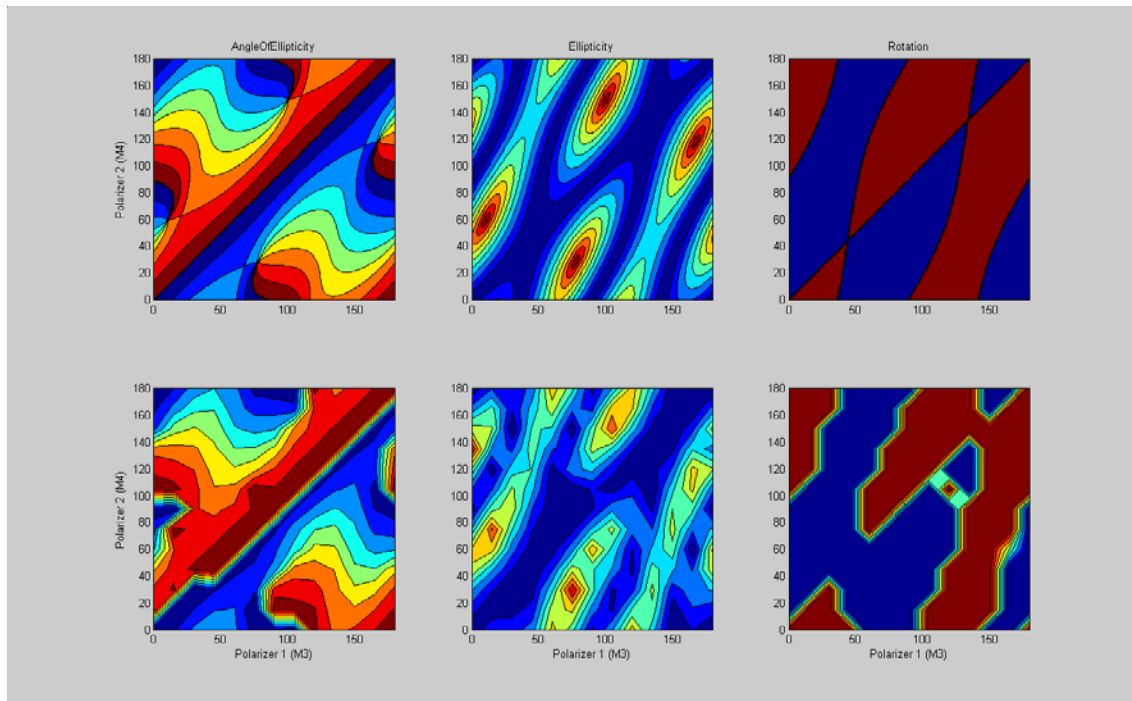


Figure 38. Upper row: Calculations, lower row: Measurements. The calculations were done in 1 degree steps and the measurements were done in 15 degree steps. This explains the rough resolution for the measurements.

2.3.12 Participation in C31 at JET

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In 2013 Morten Stejner Pedersen was on secondment at JET from May 7 to May 17 and again during C31 from June 10 to August 23. At JET he worked with the electron kinetics group fulfilling the role of deputy Responsible Officer for data analysis on the HRTS system (KE11). As such he was responsible for maintenance of the HRTS data analysis codes, for updating and implementing new calibrations for HRTS in C31 and for validation of HRTS data. This work, taking place during restart and the early part of C31 after significant changes to the HRTS system, resulted among other things in a complete update of the HRTS position and density profile calibrations. Temperature and density profiles based on the updated calibration were found to be consistent with results from other diagnostics, providing a good basis for further operation of the HRTS system in C31-C32.

In 2013 Asger Schou Jacobsen was on secondment at JET from July 15 to October 5 during the C31 campaign. At JET he worked with the neutron time-of-flight spectrometer (TOFOR) group in order to develop velocity-space sensitivity functions, also called velocity-space weight functions, for neutron spectrometers. These functions relate a given part of a measured neutron energy-spectrum to the fast-ion velocity-space distribution function. This work resulted in the development of both analytic and numeric weight functions for neutron spectrometers and neutron rate counters in general, as well as specific weight functions developed for TOFOR taking the instrumental response function into account and thus directly relate a measured time-of-flight spectrum to the fast-ion velocity distribution function.

2.3.13 The F4E framework partnership agreement on the development of a CTS diagnostic for ITER

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In the autumn of 2012, Fusion for Energy published a Call for Proposals for a framework partnership agreement (FPA) for Diagnostic Development and Design: LFS Collective Thomson Scattering. The deadline for answer was set to 30th October.

The DTU effort in 2012 was focused on forming a consortium with an appropriate partner in order to meet all the requirements to competences as well as human, financial, and managerial resources. We identified IST-IPFN as a potential partner and a very efficient and constructive collaboration was established between our two associations. The resulting answer to the Call for Proposals was submitted to F4E in due time basically fulfilling all requirements.

During 2013 the DTU effort was focused on elaborating and clarifying the scientific as well as the administrative content of the FPA in collaboration with F4E and by the end of the year a mutual satisfactory agreement was found.

In Early 2014 the contract on F4E-FPA-393 Diagnostic Design and Development: Low Field Side Collective Thomson Scattering (LFS CTS) was signed by F4E and DTU, and the evaluation of the first specific contract on planning is under way. It is expected that the involvement of DTU during the last half of 2014 will exceed 3 ppy.

The signing of the FPA contract led to a series of articles in the printed and electronic press, most prominently a full page article in Berlingske Tidende on February 20th 2014.

2.4 Publications

International journal publications

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Baiocchi, B., Mantica, P., Giroud, C., Johnson, T., Naulin, V., Salmi, A., Tala, T. & Tsalias, M. (2013) Discriminating the role of rotation and its gradient in determining ion stiffness mitigation in JET. *Plasma Physics and Controlled Fusion*. 55(2), 025010.

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Madsen, J. (2013) Gyrokinetic linearized Landau collision operator. *Physical Review E*. 87(1), 01101.

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3. Fusion Technology

3.1 Thermal stability of tungsten

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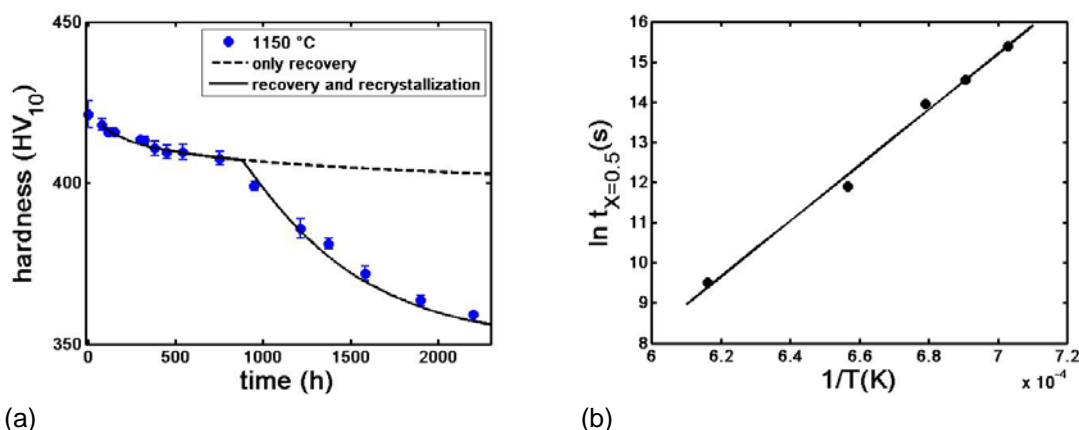
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Pure tungsten is considered as preferred candidate material for the plasma-facing first wall and the divertor of future fusion reactors due to its excellent mechanical properties, the highest melting point of all metals, a high recrystallization temperature, high heat conductivity and chemical inertness. Both parts have to withstand high temperatures during service which will alter the microstructure of the material and cause degradation of the materials properties as for example a loss in mechanical strength.

The thermal stability of a pure tungsten plate warm-rolled to 67% thickness reduction was investigated by long-term isothermal annealing for five different temperatures in the range between 1150 °C and 1350 °C up to 2200 h. The evolution of both, microstructure and texture, are characterized by electron backscatter diffraction.

During annealing, recovery and recrystallization processes cause softening of the material. Changes in hardness are quantified by Vickers hardness measurements on the rolling plane and illustrated in Figure 39a for 1150 °C. From the loss in hardness, two characteristic annealing stages are identified and confirmed by microstructural analysis using EBSD. The initial slight decrease in hardness indicating recovery (up to 750 h in case of 1150 °C) is followed by a substantial decrease showing the sigmoidal shape characteristic for recrystallization.



(a) Evolution of the Vickers hardness of 67% warm-rolled tungsten (measured in the rolling plane) with time during annealing at 1150 °C. Experimental values (blue symbols) versus predictions as a sole consequence of recovery (dashed line) and as affected additionally by recrystallization (solid line). (b) Arrhenius plot of the time to half recrystallization of the warm-rolled tungsten in dependence on temperature.

Further analysis of the kinetics in terms of classical models showed that the hardness loss during recovery can be nicely described by a logarithmic dependence on the annealing time (compare the dashed line in Figure 39a). Such behavior has been rationalized by Kuhlmann as consequence of the reduction in strength caused by dislocations due to thermally activated processes. Comparing the corresponding slopes at different temperatures an apparent activation volume of $21 b^3$ is obtained independent of temperature.

Taking into account the hardness loss during recovery, the recrystallized volume fraction is determined quantitatively and the recrystallization kinetics analyzed in terms of Johnson Mehl Avrami Kolmogorov kinetics. For a proper description of the experimental data (as seen by the solid line in Figure 39a) a temperature-dependent incubation time had to be accounted for. From Arrhenius plots of the fitting parameters for all five investigated temperatures (as illustrated in case of the time to half recrystallization in Figure 39b) activation energies can be determined for the different thermally activated processes. All obtained activation energies summarized in table 1 are comparable to the activation energy of bulk self-diffusion of 568 kJ/mol.

Table 1: Activation energies for recrystallization of a tungsten plate warm-rolled to 67% thickness reduction.

Incubation time	568 kJ/mol
Thermal activation of growth and nucleation	554 kJ/mol
Half recrystallization	576 kJ/mol

On the basis of the obtained parameters, an extrapolation to lower temperatures can be performed showing that for temperatures below 1075 °C the predicted life span before half recrystallization of the warm-rolled tungsten plate will exceed the requested lifespan for divertors of 2 years.

3.2 Nanostructuring of steels by dynamic plastic deformation

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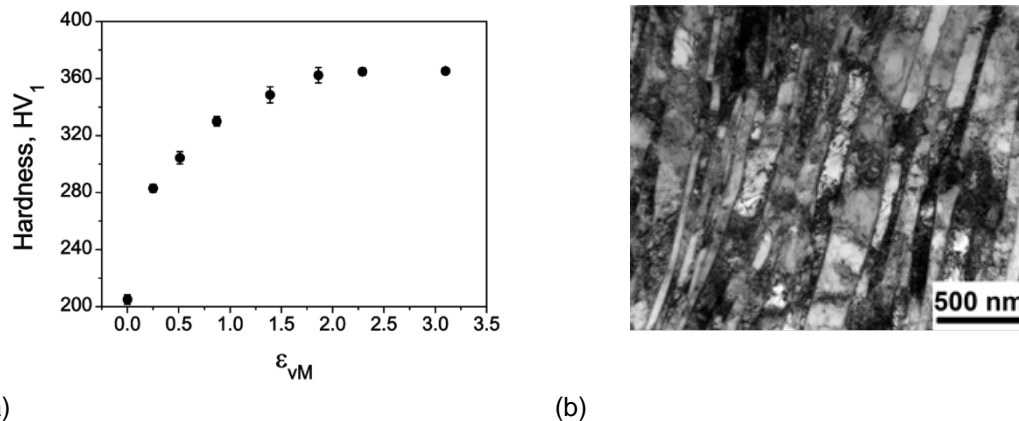
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Ferritic/martensitic steels containing 9 to 12 wt.% Cr are used as structural materials in power plants and also considered to be candidate structural materials for advanced fission and fusion reactors. Such materials must be resistant to irradiation induced swelling and retain high strength at elevated temperatures. It has been reported that materials with well-refined microstructures may exhibit improved irradiation tolerance compared to their coarse-grained counterparts.

One way to effectively refine the microstructure of the ferritic/martensitic steels is by substantial plastic deformation. In an attempt to achieve nanostructuring, samples of ferritic/martensitic steels with and without oxide dispersion strengthening (ODS) are compressed by dynamic plastic deformation (DPD) with strain rates of 10^2 – 10^3 s⁻¹. The merit of employing the DPD technique is that it not only provides high strain rates promoting grain refinement, but also allows realizing nanostructuring by repeating the process to high strain.

Samples of modified 9Cr–1Mo steel (X10CrMoVNb9-1) were compressed at room temperature by DPD to different strains. The Vickers hardness measured in the center of the samples increases with increasing strain as shown in Figure 40a: the hardness increases rapidly for strains below 1.5, but changes very little at strains above 1.5



(a) (b)
 Figure 40 Dynamic plastic deformation of modified 9Cr–1Mo steel: (a) Vickers hardness after DPD to different strains and (b) TEM image after DPD to a strain of 2.3 (from the central part of the specimen in a section that contained the compression direction).

The microstructure of two samples deformed to strains of 0.5 and 2.3 was investigated using both transmission electron microscopy (TEM) and electron backscatter diffraction. During DPD, the deformation structure evolves from a cell structure at a strain of 0.5 to a typical lamellar structure after a strain of 2.3 (see Figure 40b). The change in morphology is accompanied by a decrease in the average boundary spacing (measured along the compression axis) from 190 nm at a strain 0.5 to 98 nm at a strain of 2.3. Hence, it is demonstrated that the microstructure in the 9Cr–1Mo steel can be effectively refined by DPD.

4. DTU Contribution to EFDA-Times

4.1 Modelling fusion in existing global energy system models: EFDA-TIMES and TIAM

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EFDA-TIMES and TIAM are two variants of an optimisation model for the global energy system divided into 15-17 regions with time horizon 2100. The model framework has been developed and used by the IEA Implementing Agreement ETSAP (Energy Technology Systems Analysis Programme) since 1976. The EFDA-TIMES variant has been a key activity within the Socio-Economic Research on Fusion (SERF) programme, and this work will continue under the new EU Horizon 2020 programme, EUROfusion Consortium, Work Package Socio Economic Studies (WPSES).

The time horizon 2100 of this model will allow a significant contribution by fusion power. Forecasts of energy demands come from other global economic models focusing on population and economic growth. Technologies are organised into a network of energy flows linking demand and supply for optimisation using linear programming. The objective value is the total discounted energy system costs. Constraints include capacities of existing energy technologies, availabilities of future technologies, and environmental constraints, in particular on CO₂ emission. The typical climate constraint is the 550 ppm limit on the concentration of CO₂ equivalents. Other key parameters are investment and operation costs of fusion and competing technologies and forecasts of fuel prices.

Fusion units will operate very similar to other large-scale thermal electricity generating units, such as coal and nuclear fission. The market share for these technologies is likely to decrease,

because new renewable technologies become cheaper and abundant, in particular concentrated solar power (CSP) and off-shore wind; or small-scale units, mainly solar PV or micro CHP will be integrated in local grids. The role of fusion during the last decades of the 21st Century is very dependent of the combination of economic assumptions, ranging from zero to a significant share of large-scale base-load technologies [1].

During 2013, the economic research within Socio-Economic Research on Fusion has focused on the consolidation and exploitation of research results achieved within the 2010-12 Work Programmes, and to finding the ways to increase a political interest in fusion [2].

Following the agreement in 2012 between the EFDA Leader and ETSAP, the EFDA-TIMES team has contributed to the collaboration on the TIAM model. A video link was established to the ETSAP meeting in Seoul in November 2013 [3-6], http://www.iea-etsap.org/web/Seoul_Nov2013.asp.

[1] Grohnheit, P.E.; Korsholm, S.B. (2013), Development & application of ETM dissemination strategies. Socio Economic Research on Fusion. EFDA Technology Workprogramme 2012. WP12-SER-ETM-3-01.

[2] Grohnheit, P.E. (2013), ETM documentation update – including modelling conventions and manual for software tools. EFDA TIMES WP13-SER-ETM D.2.2.

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[6] Grohnheit, P.E.(2013), Impact of technology and regional specific discount rates

[3-6] Presented at EFDA TIMES Workshop 4 November 2013, DTU Risø Campus, Roskilde, Denmark / video link to the 64th Semi-annual ETSAP meeting, Seoul, Republic of Korea.

5. Industry awareness activities towards ITER

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed and maintained in 2006-2010. In 2009 public funds in the order of 1 M Euro over three years was granted to the Danish Big Science Secretariat (BSS); fostered at and administered by DTU. In 2012, a successful effort to secure funds for a continuation of BSS (2013-2015) was completed. BSS is described in more detail below.

The Danish representative of the F4E ILO network is Søren B. Korsholm of Association Euratom -DTU. The network now comprises 19 European ILOs. During 2013 the tasks and procurements from the ITER Organisation (IO) and F4E have received some attention from Danish companies, and a few bids and expression of interests have been placed during 2013 – still so far without success on the industrial side. On the scientific side DTU secured the F4E-FPA-393 on development of the CTS diagnostic for ITER as described elsewhere in this report. The opportunities for participation in procurements and events are announced via the webpage and newsletter of the Big Science Secretariat.

5.1 The Big Science Secretariat – Denmark

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With offset in the DTU initiative on promoting the ITER industrial opportunities to Danish companies, a partnership was made (2009-2012) between DTU, FORCE Technology, and Teknologisk Institut (DTI – Danish Technological Institute) – both latter are non-profit technology service institutes. The aim of the partnership was to create a unit and a project which aims at increasing the Danish industrial involvement in the construction of (European) big science facilities. The project is called Big Science Sekretariatet in 'Danish' or The Danish Big Science Secretariat (BSS). The project was lead and coordinated by DTU Physics up to the end of 2012.

In 2012, negotiations between the partners and the Danish Agency for Science, Technology and Innovation lead to a continuation of the funding of BSS through a partnership between DTI and DTU running from 2013-2015 with the project coordination being transferred to DTI due to other administrative rules. Combined with additional funds relating to ESS and the Capital Region of Denmark, the total public support to BSS sums up to a total of 10 mio Danish kr. over three years. This has also lead to an expansion of the DTU staff employed at BSS.

The aim of the BSS initiative is two-fold: to increase the awareness of Danish companies on the potential for commercial participation in the construction phase of big science projects, and to assist companies in the required competence and network building phase prior to being able to bid for contracts on ITER, ESS, CERN, XFEL, ESO etc.. At the same time, BSS is connecting to the big science facilities to make the Danish company competences known to them. To facilitate this better BSS partners are now taking care of the ILO roles at F4E/ITER, ESO, CERN, and ESRF.

The pivot of the BSS project is the BSS secretariat (bi-located at DTU and at DTI) which is managed by two full time professionals and a part time communication responsible person. In addition, a number of experts at DTU and DTI are connected to BSS, in order to assist Danish companies in their need for competence building and expert advice in the preparation phase. Some awareness activities were conducted in 2013, while the emphasis has been more on targeted thematic events often with participation of big science organisations like, ESS, CERN, and ESO. The main event of 2013 was the 'Meet Danish Suppliers'-event in October where Big Science primes involved in e.g. ITER tenders (e.g. Astrium (D) and Walter Tosto (I)) came to Denmark to meet potential subcontractors among Danish companies. The event was very positively received by both primes and Danish companies.

The BSS project has received positive attention and remarks from Danish companies as well as several of the European big science facilities. The BSS project has also received quite some attention by the Danish press. Furthermore, other European countries are considering similar initiatives. A main source of news from BSS to the 125+ members and about 300 additional subscribers is the weekly BSS newsletter with news, events announcements, and lists with current tenders. In 2013, a LinkedIn group for BSS was also established and quickly reached more than 200 followers.

The project is further described in the BSS webpages www.bigscience.dk.

[1] Association Euratom - Risø National Laboratory, Technical University of Denmark, Annual Progress Report 2006.

6. Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact and assisting students to talks about fusion at different venues. A major part of the activities is normally the performances of the Fusion and Plasma Roadshow, described below, and in 2012 the participation in the national science festival was resumed. The public information EFDA task was continued in 2012 since Risø DTU and FOM in 2010 took up the EFDA task of *Interactive Exhibits for the Fusion Expo*. This task was prolonged and it is described in Section 6.2.

Over the last couple of years a good contact has been established between DTU and the national science talent center (ScienceTalerter) in Sorø. This has resulted in several talks to high school teachers and/or students. However, most importantly, ScienceTalerter received a grant to make a fusion physics master class in 2010-2011 for 25 science talents from 5 high schools. This was conducted with one initial camp for the teachers followed by two camps for the students with homework projects. This gave all participants a solid foundation in the field of fusion physics, and the master class was concluded by a 4 days travel to England in the spring of 2011 with the main attraction being a visit to JET and MAST. The event was repeated in 2012-2013 with 30 high school students from 6 high schools and the visit to JET was successfully conducted in Mid-April 2013. The feedback from high schools and students were very positive.

For brevity the further activities are put in list form below

- Popular lectures on fusion energy
- Assisting students from primary and high school in fusion oriented projects.
- Contact to journalists (web, newspapers, radio and TV) on fusion and ITER related news
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine

The most comprehensive result of the press contact was fusion research being the main topic of a full feature in Videnskabens Verden on the national Danish radio DR P1 on 15th October 2013

<http://www.dr.dk/arkivP1/Videnskabensverden/Udsendelser/2013/10/14160648.htm>

6.1 The Danish Fusion and Plasma Road Show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom-DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show was funded for three years (2007-2009) by the Danish Research Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro. Since the funds have ceased the show has been maintained and used for a series of events.

The objective of the road show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people's experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience.

In the course of the road show the following experiments are conducted:

- An exercise bike connected to a generator and an inverter to be able to supply household appliances with power produced by the bike. This is a very popular experiment, where volunteers in the audience can get a feel for how much we should work to cover our consumption.
- Jacob's Ladder: Plasma created by 10.000 V between two copper wires
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – levitated magnet above superconductor
- Plasma ball lamp

During 2013 the roadshow has been performed primarily during the National Science Festival Week in September as well as for the ScienceTalents from Sorø Academy.

6.2 Interactive Exhibits for the Fusion Expo

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FOM and DTU jointly took up the EFDA task WP09-PIN-INTEX "Creating interactive exhibits for Fusion Expo". The aim of the task is to create new and more interactive exhibits for the Fusion Expo within a number of categories. It is a multistep task, where inspiration and ideas were explored and discussed.

A range of ideas have been developed and prioritized, and the high priority ideas have been described in greater detail. All the selected exhibits is now part of the Fusion Expo that appears to be discontinued as of July 1st 2014.

The task was thus successfully finalized with a final report submitted in December 2011. However, as one of the exhibit items was the development of an iPad fusion game, and this

development was extended, the FOM and DTU representatives agreed to continue supporting the task in order to complete the last exhibit. The iPad game was released on the Apple Store in February 2014.

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